

THREE ESSAYS ON ENVIRONMENTAL ECONOMICS AND HUMAN BEHAVIOR

A Dissertation

Presented to the Faculty of the Graduate School

of Cornell University

in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

by

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August 2013

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Cornell University 2013

The first essay of this dissertation uses a general equilibrium model of the U.S. economy to study the welfare implications of a biofuel blend mandate and consumption subsidy in the presence of pre-existing labor and fuel taxes. The tax interaction and revenue recycling effects are found to be significant relative to the overall costs of the policies and to previous partial equilibrium studies. I find empirically that the tax credit is welfare superior to the mandate for a given level of ethanol consumption, and this result is robust to the presence or absence of the labor tax. The second essay studies consumer behavior in durable goods markets. I extend a classic model of consumption with status-seeking preferences to incorporate a visible durable good stock with three attributes: quality, average item age, and stock size. “Newness” is an important feature of durable goods consumption, and I illustrate how the newness of a durable good stock, as captured by average item age, could be used as the status signal in a signaling equilibrium. I analyze Consumer Expenditure Survey data on the consumption of apparel goods which vary quasi-experimentally in visibility, and my empirical results suggest that newness and/or stock size may be used more than quality as a status signal, if consumers use apparel consumption to signal income. The third essay analyzes a model in which environmental regulation can potentially satisfy the “Porter hypothesis.” I show theoretically how limited attention to waste production on the part of behaviorally-biased firm managers can result in internally sub-optimal production choices and the potential for “win-win” environmental regulation which increases net social benefits and also makes the firm itself better off.

BIOGRAPHICAL SKETCH

Kristen Cooper (née Brinley) grew up in Wheaton, Illinois. She earned her Bachelor of Arts degree in 2006 from Gordon College in Wenham, Massachusetts, with majors in Economics and Spanish and a minor in Mathematics. Kristen earned her Ph.D. in Applied Economics and Management from Cornell University in Ithaca, New York in 2013.

DEDICATION

For my family, and especially for Duncan.

ACKNOWLEDGEMENTS

I am thankful for the financial and institutional support from the Charles H. Dyson School of Applied Economics and Management at Cornell University which has allowed me to complete my doctoral studies and dissertation research. I gratefully acknowledge the Chairperson of my graduate Special Committee, Professor William Schulze, and my Special Committee members, Professors Mike Waldman and Jura Liaukonyte, and thank them for their invaluable support, guidance, and insight.

I additionally wish to acknowledge and thank Professor Harry de Gorter for his research assistance funding and direction on biofuels policy research. The essay in Chapter 1 of this dissertation reflects joint work with Dusan Drabik, my fellow Ph.D. student in Applied Economics and Management at Cornell University, and I thank him for his enjoyable co-authorship and research excellence. I acknowledge the helpful comments received when I presented our research at the Agricultural and Applied Economics Association Annual Meeting in Seattle, Washington, August 12-14, 2012, and I thank the Cornell University Graduate School for a grant to attend that conference. For valuable suggestions on the essay in Chapter 2 of this thesis, I gratefully acknowledge Professor Ori Heffetz. Finally, I wish to thank the participants in the Applied Micro Workshop at Cornell University, which is sponsored by the Gatto Economic Research & Faculty Development Fund, for their comments during my March 2013 presentation of the essay in Chapter 2 of this thesis.

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CHAPTER 1

WELFARE EFFECTS OF BIOFUEL POLICIES IN THE PRESENCE OF FUEL AND LABOR TAXES

1.1. Introduction

Biofuel blend mandates and consumption subsidies are used throughout the world. Although the U.S. blenders' tax credit expired at the end of 2011, many other countries continue to employ tax-exemptions at the gasoline pump. In this essay, we derive and compare the welfare costs and benefits of biofuel blend mandates, consumption subsidies, and their combination using a closed-economy, general equilibrium model. Our approach focuses on the interactions of biofuel policies with the labor market and fixed fuel tax. Our central finding is that fiscal interaction effects are significant relative to the overall costs of the policies.

The first part of this essay develops a theoretical general equilibrium model with a pre-existing labor tax which can be used to analyze the fiscal interaction effects of U.S. ethanol policies. The model parsimoniously captures the trade-off between corn used to produce fuel and corn used for direct consumption: corn and labor are used as inputs; ethanol and gasoline are intermediate goods; corn, fuel, and a numeraire good as consumed as final goods. The model also includes a volumetric fuel tax. Following other studies, (e.g., Cui et al. 2011, Lapan and Moschini 2012), we assume that the only societal benefit of the ethanol policies is to reduce the greenhouse gas (GHG) intensity of the fuel blend.¹ Unlike Cui et al. (2011) and Lapan and Moschini (2012), we take the price of gasoline to be exogenous, and our closed economy precludes terms of trade effects in oil imports and corn exports.

¹ This simplifying assumption ignores other environmental externalities associated with fuel consumption, including traffic congestion, motor vehicle accidents, or local air pollution (Parry and Small 2005, Parry et al. 2007, Khanna 2008; de Gorter and Just 2009b; 2010a; 2010b), as well as the concerns related to energy security.

A rich literature in public finance and environmental economics has shown that the interaction of environmental policies with the broader fiscal system can significantly affect welfare measures in the context of environmental externalities (e.g., Bovenberg and de Mooij 1994, Parry 1995, Goulder et al. 1999, Parry and Small 2005, West and Williams 2007). The fiscal interaction effect of an environmental policy consists of the “tax interaction effect” and “revenue-recycling effect.” The tax interaction effect arises when biofuel policies change the relative commodity prices (corn and fuel, in our model) with respect to the price of labor which in turn affects demand for leisure, labor’s substitute. This first-order welfare effect due to a change in the labor tax base occurs because of the pre-existing distortion in the labor market (Browning 1987, Parry 1995). The revenue-recycling effect arises because biofuel policies affect government revenue from the fuel market, and fuel market revenue is a substitute for labor tax revenue. Assuming that the level of total government spending will be held fixed, a biofuel policy which increases (decreases) government revenue from the fuel market will cause a decrease (increase) in the labor tax rate. The welfare effect of such a change in the labor tax is known as the “revenue-recycling effect” (Goulder 1995).

In the second part of the essay, we calibrate the model to the U.S. market conditions in 2009 to investigate how important fiscal effects are relative to the overall welfare effects of the biofuel policies. If fiscal interaction effects are relatively large, research efforts which ignore them may overestimate the net benefits of the policies (if the fiscal interaction effects are negative), or underestimate the benefits (if the policies yield a “double dividend” – i.e., their net fiscal interaction effects are positive (Bento and Jacobsen 2007, Parry and Bento 2000)).

Using the numerical model, we first determine the optimal level of the tax credit or mandate, and we find that both policies would optimally be zero. This result is primarily due to

rectangular deadweight costs (RDC) resulting from ‘water’ in the ethanol price premium. The ethanol price premium is the gap between the observed ethanol price and the ‘no policy’ ethanol price which would prevail in the absence of any biofuel policies; if the ‘no policy’ ethanol price is not high enough to induce ethanol production, ‘water’ is defined as the lower range of the price premium which contains the ethanol prices at which no ethanol would be produced.

We perform three other types of policy analysis using the numerical model. First, we study the welfare effects of removing a tax credit which is used in combination with a binding mandate (which mirrors the expiration of the U.S. blenders’ tax credit at the end of 2011). We find that removing the tax credit while keeping the mandate in place results in a welfare improvement of \$9 million. Next, we analyze the welfare effects of the blend mandate alone. We find that the mandate imposes a welfare cost of \$8.3 billion relative to an equilibrium where there is no ethanol policy. In these policy analyses, we make use of results from our theoretical model which allows us to separate the total welfare effect into four components: the primary distortion, the two fiscal interaction effects, and an externality effect. We find that most of the mandate’s cost can be attributed to the primary distortion, although the tax interaction effect of \$1.54 billion is also significant. Our finding that the status quo policies incur significant welfare costs corroborates our finding that the optimal policies are both zero.

Our third policy analysis compares the welfare under a mandate *versus* a tax credit for the same ethanol production. The question of which policy is superior has important implications for all countries which use biofuel policies, and this essay is the first to compare them in a general equilibrium framework. Theoretical partial equilibrium models (Lapan and Moschini 2012, de Gorter and Just 2010b) have shown that the mandate is superior to the tax credit on a welfare basis. Lapan and Moschini (2012) derive the optimal biofuel policies in the presence of a pre-

existing fuel tax and find that the optimal second-best mandate welfare dominates the optimal second-best subsidy alone. We cannot compare the mandate and the tax credit on the basis of welfare at their optimal levels – as analyzed by Lapan and Moschini (2012) – because we find both policies to be zero in the optimum due to RDC.

When we compare the welfare associated with the tax credit and mandate for the same ethanol production, we find empirically that the blenders' tax credit is welfare superior to the mandate. This ordering is found to hold regardless of RDC. This is a novel result, since de Gorter and Just (2010) conclude that a mandate always welfare dominates the tax credit, given the same ethanol production. Our finding that the tax credit welfare dominates the mandate is driven by the fact that the fuel tax exceeds the marginal external cost of GHG emissions and so is superoptimal. Because the mandate by itself acts as an implicit tax on fuel consumption, its implementation on top of a superoptimal fuel tax makes it even more distortionary. On the other hand, because the tax credit lowers the fuel price, it works in the opposite direction and brings the effective fuel tax closer to its optimal level. When we compare the policies in a framework where there is no fuel tax, we find that the mandate is slightly superior to the tax credit.

Previous research has shown that differences in environmental policies' effects on government revenue can influence their welfare ordering (Goulder et al. 1997, Goulder et al. 1999). There are several inherent differences between biofuel blend mandates and consumption subsidies that make their fiscal interaction effects likely to differ. For example, although both the tax credit and mandate are revenue-requiring policies for a given level of ethanol (since fuel tax revenue declines with a mandate), the relative fiscal effects are *a priori* indeterminate. Fuel prices are always relatively higher under a mandate, and corn prices are the same for a given level of ethanol production, which implies that the mandate has a more costly tax interaction

effect. We compare the mandate to the tax credit in a framework with a fuel tax but no pre-existing labor tax, and we find that the tax credit is still superior in this case.

The majority of literature studying the welfare effects of biofuel policies has taken a partial equilibrium approach (Rajagopal et al. 2007, Khanna et al. 2008, de Gorter and Just 2009b, Cui et al. 2011, Lapan and Moschini 2012). Several partial equilibrium studies estimate optimal biofuel policies and find varying results, due largely to their inclusion of different externalities. For example, Khanna et al. (2008) study a partial equilibrium model where vehicle-miles-traveled (VMT) cause congestion and emissions externalities. They find that the first-best policy combination includes a negative ethanol subsidy – a \$0.04/gallon tax – since a positive ethanol subsidy decreases the price of the fuel blend and worsens the congestion externality. On the other hand, Vedenov and Wetzstein (2008) assume that ethanol consumption improves environmental quality and fuel security relative to gasoline; they follow an approach similar to Parry and Small (2005) and find that the optimal ethanol subsidy is \$0.22/gallon.

Cui et al. (2011) analyze optimal biofuel policies in the presence of an emissions externality only and find that the optimal ethanol tax credit is \$0.67/gallon in 2009 (35 percent greater than its actual level of \$0.49/gallon) and that the optimal mandate yields even greater ethanol production than the optimal tax credit. Although our empirical model includes the same externality and is calibrated to 2009 U.S. data, we find the optimal tax credit or mandate to be zero. There are three main drivers of this difference. First, ethanol policies in the Cui et al. model derive additional benefits from the terms of trade effects in the oil and corn markets, which our closed economy model does not capture.² Second, our ethanol policies have greater welfare

² Previous literature about the welfare effects of biofuel policy has also discussed the issue of “leakage” in the corn (e.g., Al-Riffai et al. 2010) and ethanol (Drabik et al. 2010; Rajagopal et al. 2011; Khanna 2012) markets and suggested that the leakage may be a significant component of welfare. Although we do not analyze leakage in this

costs because we interact them with a pre-existing labor tax and fixed government revenue requirement. Finally, the status quo ethanol policies in Cui et al. (2011) are associated with lower deadweight costs because of the absence – relative to our model – of RDC.

Although the literature on fiscal interaction effects is extensive, few papers have measured the fiscal interaction effects of biofuel policies.³ Crago and Khanna (2012) study the welfare effects of a carbon tax where a pre-existing ethanol subsidy and labor tax may be present; our approach here is to study the welfare effects of ethanol policies directly. Devadoss and Bayham (2010) also use a general equilibrium model to analyze welfare effects in biofuels markets, but they study the effect of the U.S. crop subsidy rather than the biofuel policy directly, and they do not have a labor market distortion. Taheripour and Tyner (2012) analyze the welfare effects of an ethanol quantity mandate in an open-economy general equilibrium framework using the GTAP-BIO-AEZ model; they model the mandate by imposing a combination of market incentives necessary to induce the mandated quantity of ethanol. We implement the blend mandate directly in our model—that is, we do not require any additional policies to generate the mandated ethanol consumption.

Overall, this essay contributes to the biofuel policy literature in two ways. First, we estimate the welfare effects of the tax credit and mandate using a general equilibrium model that allows us to estimate the fiscal interaction effects of each policy. We find that the fiscal interaction effects are significant relative to the overall costs of the policies. Because the tax credit was not the binding policy in most of 2009, its removal yields a total welfare gain of only \$9 million; however, the net fiscal interaction effect of this policy shock is considerably higher

essay, in section 4.6 we do discuss the implications of leakage on the change in fuel tax revenue due to biofuel policies.

³ Studies that have analyzed the fiscal interaction effects of other agricultural policies include Parry (1999) and Taheripour et al. (2008).

and represents a gain of \$357 million. The welfare cost of the remaining mandate is \$8.3 billion, which includes a tax interaction effect of \$1.54 billion. Our second finding is that the tax credit is welfare superior to the mandate for the same ethanol production when the fuel tax is superoptimal. This extends the partial equilibrium results of de Gorter and Just (2010b).

The remainder of the chapter is organized as follows. In the next section, we build an analytical closed-economy general equilibrium model. In section 1.3, we derive analytical expressions for the marginal welfare effects of each biofuel policy independently as well as effects of the tax credit applied in the presence of a binding mandate. Section 1.4 presents a numerical version of the model; the data and calibration method for the numerical model are presented in section 1.5. Section 1.6 presents our results, and section 1.7 concludes.

1.2 Analytical Model

The Representative Consumer

The representative consumer consumes fuel F , corn C , numeraire good x , and leisure N .⁴ Leisure is assumed to be weakly separable from consumption of goods in utility. The consumer receives disutility $\sigma(\cdot)$ from an externality R associated with fuel consumption, whose nature is discussed further below. The externality is assumed to be separable in utility; this assumption implies that the consumption-leisure trade-off is not affected by the level of environmental quality (Goulder et al. 1999). We have chosen the consumption bundle and utility assumptions so that the model can capture the interaction effects in which we are interested yet remain tractable.

The utility function is given by:

$$U = \varphi(u(F, C, x), N) - \sigma(R). \quad (1)$$

⁴ Fuel is a mixture of ethanol and gasoline. Because one gallon of ethanol has lower energy content than the same amount of gasoline, we measure fuel consumption in gasoline energy-equivalent gallons (GEEGs).

where $\varphi(.)$ denotes utility from the consumption goods and leisure.

Production

Labor is the only factor of production, and the representative consumer's time endowment is \bar{L} . The consumer allocates his time between labor L and leisure such that $L + N = \bar{L}$. Labor is used in the production of gasoline G , ethanol e , corn supply C^S , and the numeraire good. The quantities of labor used to produce each good are L_G , L_e , L_C , and L_N , respectively. The wage rate is denoted by w .

Gasoline and the numeraire are produced by constant returns-to-scale production technologies. We assume perfect competition in the production of both goods, so the prices of gasoline and the numeraire depend only on the wage rate. Corn is produced using labor according to a decreasing returns-to-scale technology $f(.)$:

$$C^S = f(L_C). \quad (2)$$

Profits from corn production are denoted by π_C and are returned lump-sum to the consumer.⁵

Ethanol e (quantity measured in physical gallons) is produced from corn and labor according to a fixed coefficients production process:

$$e = \min\{e_C C^e, e_L L_e\}. \quad (3)$$

where C^e is the residual corn supply after corn consumption demand is met: $C^e \equiv C^S - C$; the parameter e_C denotes total gallons of ethanol produced from one bushel of corn, and e_L denotes gallons of ethanol produced per unit of time. When calibrating the model to observed data, we assume that the co-product from ethanol production (Dried Distillers Grains with Solubles) is a perfect substitute for corn.

⁵ Positive profits in corn production follow from our definition of the ethanol supply curve as the horizontal difference between the corn supply curve and the non-ethanol demand curve for corn. The positively sloped corn supply curve implies positive profits.

The zero profit condition for ethanol production determines the link between ethanol and corn prices, denoted by P_e and P_C , respectively⁶:

$$P_e = P_C / e_C + w / e_L . \quad (4)$$

The link between the amount of labor and corn needed to produce e gallons of ethanol is obtained from cost minimization:

$$e = e_C C^e = e_C (C^S - C) = e_L L_e . \quad (5)$$

The consumer buys a blend of gasoline and ethanol. We assume that the consumer values fuel for miles traveled. Since one gallon of ethanol yields fewer miles than a gallon of gasoline, we let γ denote the ratio of miles traveled per gallon of ethanol and gasoline. Total fuel consumption measured in gasoline energy-equivalent gallons (GEEGs) is then given by $F = G + \gamma e$. Following de Gorter and Just (2008), we assume that $\gamma = 0.7$. Throughout our analysis we use $E = \gamma e$ to denote ethanol measured in GEEGs. We assume that the fuel blend is produced by competitive blenders earning zero profits who face exogenous gasoline market price P_G and the ethanol market price $P_E = P_e / \gamma$, where P_E denotes the ethanol price in \$/GEEG.

Externalities

Fuel consumption is assumed to produce only one externality, carbon dioxide (CO_2) emissions; we allow the emissions per consumed GEEG to differ between ethanol and gasoline.⁷ We normalize the units of CO_2 emissions so the externality can be written as:

$$R(G, E) = G + \xi E . \quad (6)$$

⁶ The parameter e_C takes into account the effect of the ethanol co-product on the corn price.

⁷ Other externalities associated with fuel consumption, such as traffic congestion or motor vehicle accidents, arise from vehicle-miles traveled (VMT) rather than fuel combustion. If ethanol is measured in GEEG, its VMT externalities do not differ from those of gasoline. In our model, the only potential benefit from ethanol relative to gasoline is reducing emissions (see also footnote 1). In our numerical model, we find that an extremely high MEC of carbon would make the optimal ethanol policies positive.

where ξ denotes relative emissions of ethanol per GEEG. In the numerical part of the chapter, we assume $\xi = 0.8$, meaning that one GEEG of ethanol emits 20 percent less CO₂ than gasoline.

Government

The government employs a volumetric fuel tax t , a proportional tax on labor earnings t_L , and either a volumetric ethanol blenders' tax credit t_c or an ethanol blend mandate θ which dictates the minimum share of ethanol in the fuel (ethanol and gasoline) blend. Profits from corn production are not taxed. Real government revenue Γ is a fixed lump-sum transfer to consumers, and the government's budget is balanced and satisfies:

$$\Gamma = t_L wL + t(G + e) - t_c e. \quad (7)$$

The first term on the right-hand side of equation (7) represents government receipts from taxing labor; the second term denotes tax revenues from fuel consumption; the final term denotes expenditures on the tax credit. To hold the real lump-sum transfer Γ fixed, the labor tax is adjusted in response to biofuel policy changes (i.e., when either the tax credit or the mandate is changed and ethanol consumption, labor supply, and other variables in the model respond, the new labor tax is the one which generates the original government transfer). The fuel tax is assumed to be held constant.

Equilibrium

The assumption of perfect substitutability between gasoline and ethanol (on a miles-traveled basis) implies the following relationship between prices if the tax credit is the binding biofuel policy (de Gorter and Just, 2009a; Cui et al., 2011; Lapan and Moschini, 2012):

$$P_F = P_G + t = P_E + t/\gamma - t_c/\gamma. \quad (8t)$$

Recall that the volume of one GEEG of ethanol is more than one gallon; since the fuel tax and ethanol tax credit are both volumetric, adjusting them by γ converts them to \$/GEEG units.

In the situation when the blend mandate θ (in energy terms) determines the ethanol price, the fuel price paid by consumers is a weighted average of the ethanol price and gasoline price⁸:

$$P_F = \theta(P_E + t/\gamma - t_c/\gamma) + (1 - \theta)(P_G + t). \quad (8m)$$

A key difference between the binding tax credit and the binding blend mandate model is how the corn price is determined. With a tax credit, corn prices are directly linked to the gasoline price. Combining equations (4) and (8t) and invoking $P_e = \gamma P_E$, we see that the tax credit directly affects the corn price:

$$P_C = e_c [\gamma P_G - (1 - \gamma)t + t_c] - e_c w / e_L. \quad (9)$$

With a binding mandate, corn-market clearing determines the corn price P_C , where the corn output supply function, denoted by $g(P_C)$ in equation (10), equals the sum of consumer demand for corn and the corn required for ethanol production (where ethanol production in turn depends on fuel demand):

$$g(P_C) = \theta F(P_C, \cdot) / \gamma e_c + C(P_C, \cdot). \quad (10)$$

The dot in equation (10) denotes all remaining arguments of the corn demand function. Note that with either policy in place, corn producer's profits can be expressed as a function of the corn price and the wage rate:

$$\pi_C = P_C g(P_C) - f^{-1}(g(P_C))w \equiv \pi_C(P_C, w). \quad (11)$$

where f^{-1} denotes the inverse of function defined by equation (2).

We close the model by specifying the labor market clearing condition:

$$L_G + L_x + L_C + L_e = L. \quad (12)$$

and the representative consumer's budget constraint:

⁸ The blend mandate in energy terms denotes a share of the energy of ethanol in the total energy of the fuel.

$$P_F F + P_C C + P_x x + \omega N = \omega \bar{L} + \Gamma + \pi_C. \quad (13)$$

Consumer wealth, on the right-hand side of equation (13), includes (i) the after-tax value of the labor endowment, where $\omega \equiv (1 - t_L)w$, (ii) the government transfer, and (iii) profits from corn production; all three terms are exogenous from the perspective of the consumer.

1.3 Marginal Welfare Effects of Biofuel Policies

In this section, we present analytical formulas to identify (and later quantify) the marginal welfare effects of the biofuel policies. In our welfare effect expressions, we use the term M to denote the marginal excess burden of taxation in the labor market, which is defined for a marginal change in the labor tax rate as the ratio of the marginal change in the “wedge” distortion (numerator) and the marginal change in labor tax revenue (denominator):

$$M = -(t_L \partial L / \partial t_L) / (L + t_L \partial L / \partial t_L). \quad (14)$$

Derivations of the welfare formulas can be found in Appendices 1 to 3.

Marginal welfare effects of the blenders' tax credit

The marginal welfare effect of the blenders' tax credit can be expressed as:

$$\begin{aligned} -(1/\lambda)(dV/dt_c) = & - \underbrace{\left[(t - t_c) de/dt_c + t dG/dt_c \right]}_{\text{Primary distortion effect}} - \underbrace{(M + 1)t_L e_c \left(\partial L / \partial P_C + C^S \partial L / \partial \pi_C \right)}_{\text{Tax-interaction effect}} \\ & + \underbrace{M \left[e - (t - t_c) de/dt_c - t dG/dt_c \right]}_{\text{Revenue-recycling effect}} + \underbrace{(\sigma' / \lambda) \left(dG/dt_c + \xi \gamma de/dt_c \right)}_{\text{Externality effect}}. \end{aligned} \quad (15)$$

The first component on the right-hand side of equation (15) represents *primary distortions* or “wedges” in the fuel market caused by the fuel tax and the tax credit. It corresponds to the deadweight loss associated with the volumetric fuel tax levied on all fuel. Because the fuel is a mixture of ethanol and gasoline, the first term, $(t - t_c) \times de/dt_c$, represents the part of the change in the primary distortion effect attributable to ethanol while the term $t \times (dG/dt_c)$ represents gasoline's portion. Note that $(t - t_c)$ denotes the net volumetric fuel tax to

ethanol which is ambiguous in sign and depends on the relative size of the fuel tax and the tax credit; this term is negative in our empirical analysis.

The second component in equation (15), labeled as the *tax interaction effect*, represents the change in the labor supply (i.e., labor tax base) due to a change in the price level in the economy. When the prices of consumption goods change, the consumer reallocates the time endowment between leisure and labor. Recall that in our model the fuel price under the tax credit does not respond to shocks in this policy because it is directly linked to the exogenous gasoline price. Moreover, the price of the numeraire is normalized to unity which means that the price level in this policy scenario is changed only by the corn price. Labor supply depends on the prices of other goods, consumer wealth, and the after-tax wage rate (where the term t_L represents the wedge between pre-tax and after-tax wages). A change in the corn price due to the tax credit directly affects labor supply through the term $\partial L / \partial P_C$. The corn price change also affects corn production profits, which leads to an indirect income effect on labor supply; this is reflected in the term $C^S \times \partial L / \partial \pi_C$, where $C^S = d\pi(P_C) / dP_C$ by Hotelling's lemma.

The third component represents the *revenue-recycling* effect of the tax credit. A change in the policy gives rise not only to the primary distortion effect (in the form of a change in the deadweight loss due to the fuel tax), but also to a change in fuel tax revenue. Any change in revenue gets recycled in a revenue-neutral manner in the labor market, hence the similarity between the primary distortion and the revenue-recycling effects in equation (15).⁹ It should be noted that if the tax credit is increased (reduced), it applies to the entire new equilibrium quantity of ethanol, not only the incremental amount. This is why the term e is present; it represents the initial amount of ethanol in the revenue-recycling component of equation (15).

⁹ This also applies to equations (16) and (17).

The last component in equation (15) reflects the externality effect of a change in the tax credit. The bracketed term accounts for the change in the total carbon emissions due to a change in the tax credit. We assume that one gasoline energy-equivalent gallon of ethanol (adjusted from gallons of ethanol by the parameter γ) emits only $\xi = 80$ percent of carbon emissions relative to the same amount of gasoline. This value is close to the central estimate of 0.75 used in Cui et al. (2011). The term σ'/λ represents the marginal dollar value of a unit of the externality.

Finally, note that this marginal effect formula holds for “interior” tax credit changes that move the economy from one equilibrium where ethanol is produced to another equilibrium where more ethanol is produced. As discussed in section 1.4 below, there are many equilibria in the model where no ethanol is produced because it is too costly.

Marginal welfare effects of a binding blend mandate, holding the tax credit fixed

Unlike the blenders’ tax credit case, where the ethanol and fuel prices are directly linked to the price of gasoline, under the blend mandate both prices are endogenously determined in the market equilibrium. This implies additional complexity for the formula (16) that decomposes the welfare effects of the blend mandate, as well as for formula (17) that parcels out the effects of the tax credit for a given mandate level. Because not all the welfare effects in equations (16) and (17) can be algebraically simplified by decomposing the total fuel into gasoline and ethanol (as was the case for the tax credit), we express all the effects in terms of fuel quantity F . The marginal welfare effect of a binding blend mandate, holding the tax credit fixed, can be expressed as:

$$\begin{aligned}
-(1/\lambda)(dV/d\theta) = & \underbrace{\left[F dP_F/d\theta - e\gamma dP_E/d\theta + t(1-1/\gamma)(F + \theta dF/d\theta) - t dF/d\theta + t_c de/d\theta \right]}_{\text{Primary distortion effect}} \\
& - (1+M)t_L \underbrace{\left[\left(\partial L/\partial P_C + C^S \partial L/\partial \pi_C \right) dP_C/d\theta + \left(\partial L/\partial P_F \right) (dP_F/d\theta) \right]}_{\text{Tax interaction effect}} \\
& + M \underbrace{\left\{ t(1-1/\gamma)(F + \theta dF/d\theta) - t dF/d\theta + t_c de/d\theta \right\}}_{\text{Revenue recycling effect}} \\
& + \underbrace{\left(\sigma'/\lambda \right) \left(dF/d\theta + \gamma(\xi-1)de/d\theta \right)}_{\text{Externality effect}}.
\end{aligned} \tag{16}$$

The primary distortion effect of the blend mandate in equation (16) can be thought of as the sum of three separate effects. First, the mandate by itself acts as an implicit tax on fuel; a change in the mandate also changes the effective fuel tax which corresponds to a price component of primary distortion represented by the term $F dP_F/d\theta - e\gamma dP_E/d\theta$. Second, a higher mandate requires that the volume of fuel which is taxed to meet a fixed fuel demand in GEEGs is increased, since the energy content of ethanol is lower than that of gasoline; this is reflected in the term $t(1-1/\gamma)(F + \theta dF/d\theta)$. The third impact is a quantity distortion effect, represented by $t_c de/d\theta - t dF/d\theta$; it captures the marginal deadweight loss from the tax credit and fuel tax which result from ethanol and fuel quantities responding to the policy change.

The tax interaction effect in equation (16) is akin to that in equation (15), with the exception that the mandate also affects the fuel price which in turn partially influences labor supply via the real wage. The interpretations of the revenue-recycling and externality effects in equation (16) are parallel to those for equation (15).

Marginal welfare effects of the tax credit, holding the binding blend mandate fixed

Most countries have had biofuel consumption subsidies combined with binding mandates.¹⁰ As these subsidies vary over time (e.g., the tax exemption for biodiesel in Germany has been gradually reduced), it is important to understand the welfare effects of a change in the subsidy under a binding mandate. For example, we use equation (17) to analyze the effects of allowing the U.S. tax credit to expire, akin to the expiration at the end of December 2011. The marginal welfare effect of a tax credit, holding the binding blend mandate fixed, can be expressed as:

$$\begin{aligned}
-(1/\lambda)(dV/dt_c) = & \underbrace{\left\{ F dP_F/dt_c - e\gamma dP_E/dt_c + e + t_c de/dt_c - t dF/dt_c + t\theta(1-1/\gamma)dF/dt_c \right\}}_{\text{Primary distortion effect}} \\
& - \underbrace{(1+M)t_L \left[\left(\partial L/\partial P_C + C^S \partial L/\partial \pi_c \right) dP_C/dt_c + \left(\partial L/\partial P_F \right) (dP_F/dt_c) \right]}_{\text{Tax interaction effect}} \\
& + \underbrace{M \left\{ e + t_c de/dt_c - t dF/dt_c + t\theta(1-1/\gamma)dF/dt_c \right\}}_{\text{Revenue recycling effect}} \\
& + \underbrace{\left(\sigma'/\lambda \right) \left(dF/dt_c + \gamma(\xi-1)de/dt_c \right)}_{\text{Externality effect}}.
\end{aligned} \tag{17}$$

The primary distortion effect in equation (17) follows a similar pattern to that of equation (16); the tax credit induces both price distortion effects (reflected by $F dP_F/dt_c - e\gamma dP_E/dt_c$) and quantity distortion effects (reflected by $e + t_c de/dt_c - t dF/dt_c$). The tax credit also affects the distortion between the taxed volume of fuel and consumed GEEGs of fuel, as reflected by the term $t\theta(1-1/\gamma)dF/dt_c$; note that the magnitude of this impact is proportional to the fixed mandate level. It is interesting to note that the tax credit when combined with a binding mandate can affect the fuel price, unlike when the tax credit is the binding policy. Like equation (16), the equation (17) tax interaction effect includes the labor supply response to the fuel price as well as

¹⁰ Although the U.S. corn ethanol blenders' tax credit expired on December 31, 2011, many EU countries still use tax exemptions.

the corn price, and the remaining two welfare effects in equation (17) have parallel interpretations to their equation (15) counterparts.

1.4 Numerical Model

To estimate and empirically analyze the welfare effects of a change in the U.S. biofuel policies, we develop a numerical version of the analytical model presented in section 1.2 and calibrate it to the U.S. economy in 2009.

Consumption

We assume a nested constant elasticity of substitution (CES) utility function:

$$U = U(F, C, x, N, R) = \left(\alpha_N N^{\frac{\delta-1}{\delta}} + (1 - \alpha_N) X^{\frac{\delta-1}{\delta}} \right)^{\frac{\delta}{\delta-1}} - \sigma(R).$$

where α_N is a share parameter, δ denotes elasticity of substitution between leisure and the composite consumption good, X (i.e., the CES aggregator). The composite good includes fuel, corn, and the numeraire good:

$$X \equiv \sigma_X \left(\alpha_F F^{\frac{\delta_x-1}{\delta_x}} + \alpha_C C^{\frac{\delta_x-1}{\delta_x}} + (1 - \alpha_F - \alpha_C) x^{\frac{\delta_x-1}{\delta_x}} \right)^{\frac{\delta_x}{\delta_x-1}}.$$

where σ_X is a scale parameter and δ_x reflects the elasticity of substitution among fuel, corn, and the numeraire good.

The consumer maximizes his utility subject to the budget constraint:

$$P_F F + P_C C + P_x x + \omega N = \omega \bar{L} + P_X \Gamma + \pi_C.$$

where P_X denotes the price index of the composite consumption good and Γ is the real government transfer. Derivations of the demand functions and other elements of the numerical model can be found in Appendix 4.

Production

a. Corn Production

Corn is produced by a decreasing returns to scale technology of the form $C^S = AL_C^{\varepsilon_S}$, where A is a scale parameter and $\varepsilon_S \in (0,1)$. The parameter ε_S implies that the corn supply curve is upward sloping; hence, corn producers earn positive profits. Profit maximization implies the following labor demand function L_C , output supply function C^S , and profit function π_C :

$$L_C = \left(\frac{w}{\varepsilon_S A P_C} \right)^{\frac{1}{\varepsilon_S - 1}}; C^S = A \left(\frac{w}{\varepsilon_S A P_C} \right)^{\frac{\varepsilon_S}{\varepsilon_S - 1}}; \pi_C = w \left(\frac{1}{\varepsilon_S} - 1 \right) \left(\frac{w}{\varepsilon_S A P_C} \right)^{\frac{1}{\varepsilon_S - 1}}.$$

b. Ethanol Production

The ethanol production function is the same as in the analytical section of the chapter, and it implies the following cost-minimizing factor demands:

$$L_e = e/e_L \text{ and } C^e = e/e_C.$$

The zero-profit condition for ethanol production yields the link between corn and ethanol prices:

$$P_C = e_C P_e - w e_C / e_L.$$

c. Gasoline and Fuel Production

We assume that gasoline is produced by a linear production technology $G = BL_G$, where B is a scale factor. Perfect competition and zero profits in the production of gasoline imply $P_G = w/B$. Fuel blenders face the gasoline price P_G . Price linkages between fuel, gasoline, and ethanol under a binding tax credit and blend mandate are given by equations (8t) and (8m), respectively.

d. Numeraire Production

The numeraire good is produced by a linear technology $x = kL_x$, where k is a scaling constant. Perfect competition and zero profits imply $P_x = w/k$.

Government

The government's real lump-sum transfer to the consumer is fixed at Γ , and the governmental budget constraint is given by:

$$P_X \Gamma = t_L w(\bar{L} - N) + t[F - e(\gamma - 1)] - t_c e.$$

where P_X denotes the price deflator on consumption.

Equilibrium

For any policy choice, the labor market must clear according to

$$L_G + L_x + L_c + L_e = \bar{L} - N.$$

1.5 Data and Calibration

We now calibrate the closed-economy general equilibrium numerical model from section 1.4 to reflect the realities of the U.S. economy in 2009. The observed data and parameter assumptions used in our calibration can be found in Appendix 6- Table A1, together with their sources. To consistently model the relationships in the fuel market, all prices and quantities are expressed in gasoline energy-equivalent gallons.

Because both the blenders' tax credit and a blend mandate were in place in 2009, it is important to determine which policy established the ethanol market price. We follow the reasoning presented in de Gorter and Just (2010b) and calibrate the model to a binding blend mandate. We calculate the ethanol blend mandate as the share of ethanol consumed in the United States and the total U.S. fuel consumption; this gives the mandate of $\theta = 0.06$. The ethanol blenders' tax credit of \$0.498/gallon consists of the federal part of \$0.45/gallon and the average of state tax credits of \$0.048 (Koplow 2009).

We assume that the United States faces a perfectly elastic supply of gasoline; hence, the gasoline price, $P_G = \$1.76/\text{gallon}$, is exogenous in our model. The observed ethanol market price of \$1.79/gallon corresponds to \$2.56/GEEG, reflecting lower mileage of ethanol relative to

gasoline. The final fuel price, $P_F = \$2.27/\text{GEEG}$, is equal to the weighted average of the ethanol and gasoline market prices adjusted for the fuel tax (\$0.49/gallon) and the tax credit; the weights represent the (energy-equivalent) shares of ethanol and gasoline, respectively, in the fuel blend. In calculating the fuel price, we recognize that both the fuel tax and the blend mandate are volumetric which requires adjusting the levels of these policies for the energy content of ethanol, hence the γ term in the equation defining P_F in Table A1.

We follow Ballard (2000) in determining the ‘time endowment’ ratio (i.e., labor endowment divided by labor supply), Φ , that makes our model yield estimates of the income elasticity and uncompensated elasticity of labor supply which are consistent with those found in the literature. Data from the U.S. Bureau of Economic Analysis indicate that the share of labor in the U.S. GDP was 0.57 in 2009. Normalizing the wage rate to unity, the previous ratio then determines the number of hours of labor. The total time endowment is in turn calculated by multiplying the parameter Φ by the number of hours spent working. Leisure demand is computed as the difference between the total time endowment and labor supply. Following the literature (e.g., Goulder et al. 1999; Parry 2011), we assume the (*ad valorem*) U.S. labor tax to be 40 percent. Following the Ballard procedure and using parameter and variable values detailed in Table A1, we arrive at $\Phi = 1.19$, which is close to Ballard’s estimate of 1.21. Full details about our use of Ballard’s procedure can be found in Appendix 5.

The outer-nest utility function parameters, which reflect the consumer’s trade-off between leisure and the composite consumption good, are derived through the Ballard procedure. For the inner nest, we assume that the elasticity of substitution among consumption goods is 0.3, which results in own price elasticities of demand for fuel and corn to be -0.289 and -0.299, respectively. Our fuel demand elasticity is close to that reported by Hamilton (2009) (-0.26) and

also to the long-run elasticity reported by a recent meta-analysis by Havránek et al. (2012). The corn demand elasticity is close to that used by de Gorter and Just (2009a) and Cui et al. (2011).

As mentioned above, we assume that ethanol emits 20 percent less carbon emissions relative to gasoline, in line with de Gorter and Just (2010b). We assume that the marginal external cost of CO₂ emissions is \$0.06/GEEG (Parry and Small 2005).

1.6 Results

Using the calibrated model, we first determine the optimal blenders' tax credit and mandate (individually) by maximizing social welfare (i.e., the representative consumer's utility). Unlike other studies (e.g., Khanna 2008, Cui et al. 2011), we find that both policies are zero at the optimum. The most important factor contributing to this result is the presence of 'water' in the status quo ethanol policy price premium and associated rectangular deadweight costs (RDC).¹¹

To discuss the concept of 'water,' three ethanol prices must be considered: the observed ethanol price P_E , the 'no policy' ethanol price P_E^* that would prevail in the absence of any biofuel policies, and the 'no ethanol' price P_{NE} that is the intercept of the ethanol supply curve. With the status quo ethanol policies, the observed ethanol price in our model is $P_E = \$2.56/\text{GEEG}$. The 'no policy' ethanol price $P_E^* = \$1.55/\text{GEEG}$ is determined by equation (8t) with a zero tax credit; since ethanol and gasoline are perfect substitutes, their prices must be the same after adjusting for the volumetric fuel tax. Hence, the ethanol policy price premium, defined as the difference between the observed ethanol price and its 'no policy' counterpart, is equal to $\$2.56/\text{GEEG} - \$1.55/\text{GEEG} = \$1.01/\text{GEEG}$. The price premium is also equal to the

¹¹ An explanation of 'water' in the biofuel policy price premium and related concepts can be found in greater detail in Drabik (2011).

marginal deadweight loss of the final unit E of ethanol produced—the consumer could have this unit of fuel for P_E^* but instead pays P_E for it.

Without ethanol policies, the volume of ethanol production depends only on the relative prices of gasoline and corn (in GEEG units). If the corn price is low enough relative to the gasoline price, then ethanol production will occur even without biofuel policies. For ethanol production to take place without biofuel policies, the intercept of the fuel-tax-inclusive ethanol supply curve must be less than the fuel-tax-inclusive gasoline price (i.e., there must be some quantity of ethanol that can be produced at lower cost than gasoline).

However, if the fuel-tax-inclusive ethanol supply curve intercept exceeds the fuel-tax-inclusive gasoline price, no ethanol production would take place in the absence of a biofuel policy. In this situation, there is ‘water’ in the ethanol price premium, where ‘water’ is the part of the ethanol price premium range that is above the ‘no policy’ ethanol price yet below the intercept of the ethanol supply curve (de Gorter and Just 2008; Drabik 2011). In this case, the marginal welfare effect of the final unit E of ethanol can be thought of as two distinct distortions: the marginal effect of increasing production from the $E - 1$ unit (captured by the difference between P_E and P_{NE}) and the marginal effect of going from zero units to positive production (captured by the difference between P_{NE} and P_E^*).

The critical element is P_{NE} , the intercept of the ethanol supply curve. The supply curve intercept reflects ethanol producers’ competition with corn consumers for the corn supply. At any corn market price, the amount of corn used for ethanol is equal to the difference between corn supply and consumer corn demand. Thus, we can think of the intercept of the ethanol supply curve as the equilibrium corn price that would arise if no ethanol were produced (after a unit adjustment from bushels to GEEGs).

In our model, we obtain $P_{NE} = \$2.07/\text{GEEG}$. The difference between P_{NE} and P_E^* is the ‘water’ in the policies: $\$2.07/\text{GEEG} - \$1.55/\text{GEEG} = \$0.52/\text{GEEG}$.¹² Our finding that $P_{NE} > P_E^*$ means that there would be no ethanol production in the status quo without biofuel policies; every bushel of corn produced has greater value to the consumer in the form of corn than in the form of ethanol. The total RDC associated with the status quo ethanol production is equal to ‘water’ multiplied by the amount of ethanol produced. We find that the RDC is equal to roughly \$4 billion ($= \$0.52/\text{GEEG} \times 7.73$ billion GEEGs).¹³ This significant deadweight loss is a central reason why the optimal policies are found to be zero in our model— it is very inefficient to produce ethanol from corn when its substitute, gasoline, is so much cheaper.¹⁴

To measure the welfare effects of the biofuel policies, we analyze three policy simulations: the status quo scenario (i.e., a binding blend mandate coupled with a tax credit); a scenario where the blend mandate is held at its status quo level but the tax credit is removed (the removal of the tax credit in this scenario mimics the policy change that occurred in January 2012 when the U.S. ethanol blenders’ tax credit expired but the corn ethanol mandate under the Renewable Fuel Standard remained in place); and a scenario with no ethanol policies. The results of these policy simulations are shown in Table A2 in Appendix 6.

Welfare Effects of the Tax Credit with a Binding Mandate

In the status quo scenario, ethanol production is determined by a binding blend mandate of 5.88 percent combined with a blenders’ tax credit of \$0.498/gallon. Table 1 decomposes the

¹² Our estimate of ‘water’ in the biofuel policy price premium is similar to the partial equilibrium estimate of \$0.76/GEEG reported by Drabik (2011). That our estimate of water is lower than that in Drabik (2011) is consistent with the empirical observation that general equilibrium effects tend to be smaller relative to those obtained from a partial equilibrium analysis.

¹³ 7.73 billion GEEGs correspond to 11.038 billion gallons of ethanol in the first column in Table A2.

¹⁴ In contrast, Cui et al. (2011) find that there would be ethanol production even in the absence of the mandate and tax credit in 2009. This difference arises because they calibrate their model to a binding tax credit; this necessitates adjusting the observed gasoline price up by \$0.32/gallon and results in no ‘water’ in the policies. Moreover, their model’s linear supply and demand curves (in contrast to our non-linear ones) make the presence of ‘water’ less likely.

total welfare change from the tax credit removal into the four components identified in section 1.2: the primary distortion effect, tax interaction effect, revenue recycling effect, and externality effect. The welfare effects presented in Table 1 correspond to a policy change from the status quo to the “tax credit removed” scenario in Table A2.

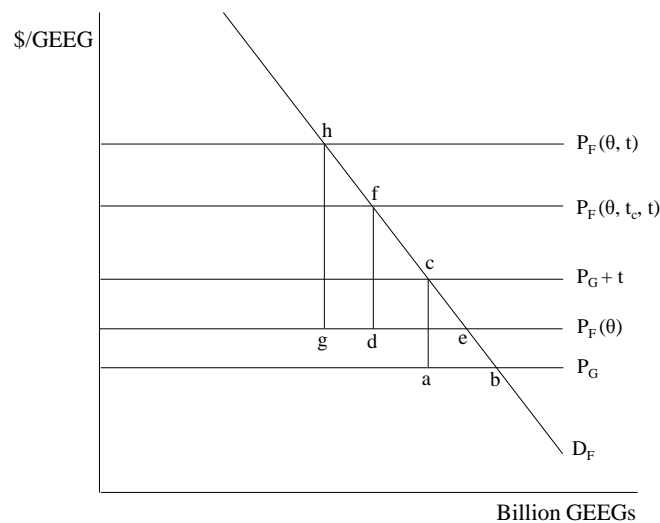
Table 1. Welfare Effects of Removing the Tax Credit but Keeping the Mandate

Welfare Component	Welfare Change (\$ billion)
Primary Distortion	-0.328
Tax Interaction Effect	-0.063
Revenue Recycling Effect	0.360
Externality Effect	0.040
Total Change in Welfare	0.009

Source: calculated

The primary distortion effect (due to the fuel tax and tax credit) in the fuel market is estimated to be a loss of \$328 million. To better understand its origin, consider Figure 1 where P_G denotes the exogenous gasoline market price, and $P_G + t$ is the consumer price of fuel

Figure 1. The Primary Distortion Effects in the Fuel Market



(gasoline) under no biofuel policies. The Harberger deadweight loss triangle associated with the fuel tax t is area abc . The fuel (ethanol and gasoline) price under a blend mandate θ alone (i.e., absent of the fuel tax and tax credit) is denoted by $P_F(\theta)$. When a tax credit t_c and a fuel tax t are added to the blend mandate, the fuel price increases to $P_F(\theta, t_c, t)$; the effective fuel tax is thus equal to $P_F(\theta, t_c, t) - P_F(\theta)$, corresponding to distance fd in Figure 1. The distortion associated with this fuel tax is therefore triangle def .

Because a mandate *per se* works as an implicit fuel tax (de Gorter and Just 2010b; Lapan and Moschini 2012), before being removed the tax credit was suppressing the full effect of the implicit tax by lowering the price of the fuel blend.¹⁵ The elimination of the tax credit increases the fuel price to $P_F(\theta, t)$, and the distortion in the fuel market is the area geh . The trapezoid $gd fh$ then represents the primary distortion effect of removing the blenders' tax credit.¹⁶

The fuel price increase lowers the real wage and causes the consumer to substitute leisure for consumption goods, thus shifting the labor supply curve to the left.¹⁷ The contraction of the labor tax base results in a welfare loss due to the tax interaction effect of \$63 million.

When the blenders' tax credit is abandoned, the government revenue from the fuel tax decreases by \$349 million (see Table A2). However, the government saves \$5.5 billion by no longer having to pay for the tax credit, so the overall revenue from the fuel market increases by \$5.15 billion. This additional revenue is "recycled" – the labor tax rate can be reduced while the real government transfer is held constant. The revenue-recycling effect of alleviating the pre-existing distortion in the labor market yields a benefit of \$360 million.

¹⁵ de Gorter and Just (2009a) show that the tax credit in combination with a binding mandate acts as a fuel consumption subsidy. Similarly, Drabik (2011) and Lapan and Moschini (2012) show that for a given blend mandate, an increase in the blenders' tax credit decreases the fuel price, but increases the gasoline price.

¹⁶ The tax credit does not cause any primary distortion in the corn market because corn is not taxed in our model.

¹⁷ Although the corn price decreases by \$0.007/bushel, this effect is more than offset by an increase in the fuel price by \$0.041/GEEG such that the overall price index rises from 1 to 1.001.

The last welfare component in Table 1 is the positive externality effect of \$40 million. This benefit is due to a decrease in fuel consumption of 710 million gallons (Table A2), caused by the elimination of the tax credit.

In total, we estimate that removing the tax credit improves social welfare by \$9 million. This result is consistent with earlier findings from partial equilibrium models (e.g., de Gorter and Just 2010b), although the magnitude of the total welfare effect is perhaps smaller than a partial equilibrium model would predict. The welfare improvement is rather small because the tax credit's removal causes a significant increase in the primary distortion in the fuel market.

The main result from Table 1 is that the removal of the tax credit (while keeping the mandate) costs \$63 million (the tax interaction effect) but there is a much bigger welfare gain due to the revenue recycling effect of \$360 million. This means the *net* fiscal interaction welfare effect is large compared to the total welfare gains and is approximately equal to the welfare loss of the primary distortion effects.

In standard models of environmental taxation, the revenue recycling effect exceeds the tax interaction effect if the taxed good is a relatively weak substitute for leisure (Parry 1995). The nested-CES functional form for we use imposes that all goods are equal (and hence all average) substitutes for leisure, so our finding that the revenue recycling effect exceeds the tax interaction effect in magnitude is perhaps surprising. However, since the tax credit was imposed on top of a binding mandate in this model, the standard model prediction does not necessarily apply and the relative size of the two fiscal interaction effects was *a priori* indeterminate.

The results presented in Table A2 also provide insights into how biofuel policies affect the fuel tax revenue. To see this, consider the addition of the tax credit to a blend mandate (the second *versus* the first column in Table A2). The increase in the tax revenue from \$65.7 billion

(= 130.04×0.49) to \$66.1 billion (= 134.75×0.49) is only due to higher fuel consumption. This means one gasoline energy-equivalent gallon of ethanol replaces less than one gallon of gasoline; thus, leakage of a biofuel policy in the fuel market is a condition for higher tax revenues.

To further analyze the role of the fiscal interaction effects in the welfare change due to the tax credit removal, we set the labor tax to zero (thus eliminating the fiscal interaction effects) and recalculate the primary distortion and externality effects (results not reported in a table). The primary distortion and externality effects are similar to those reported in Table 1—a loss of \$355 million and a gain of \$44 million, respectively. Owing to the absence of the fiscal interaction effects, however, the elimination of the tax credit results in a welfare loss of \$311 million. This indicates that when the labor tax cannot be adjusted in response to a change in the net fuel tax revenue and when the real government transfer is not held constant, adding a tax credit to a binding mandate may indeed be welfare improving. In this case, the welfare improvement occurs only due to higher fuel tax revenue which is transferred lump sum to the representative consumer.¹⁸ Because the ethanol price is determined by the mandate, the addition of the tax credit has only a marginal effect on ethanol consumption, and (mostly) gasoline consumption is subsidized instead. This gives rise to higher fuel tax revenues.

Welfare Effects of Blend Mandate Removal

We now quantify how welfare would change if the status quo blend mandate were removed, and no tax credit was in place. This is the welfare effect of a change from the second scenario in Table A2 (*Tax Credit Removed*) to the third scenario (*No Ethanol Policy*). We anticipate that removing the mandate will cause welfare gains since we find that the optimal blend mandate is zero. Table 2 presents our estimates of the total welfare effect as well as its

¹⁸ This is analogous to Cui et al. (2011) where the status quo versus a tax credit results in significant welfare gains due to increased tax revenues.

components. The last row of Table 2 does indeed confirm that overall welfare improves by \$8.28 billion when the mandate is removed.

Table 2. Welfare Effects of Removing the Mandate after Tax Credit is Removed

Welfare Component	Welfare Change (\$ billion)
Primary Distortion	6.974
Tax Interaction Effect	1.544
Revenue Recycling Effect	-0.063
Externality Effect	-0.173
Total Change in Welfare	8.282

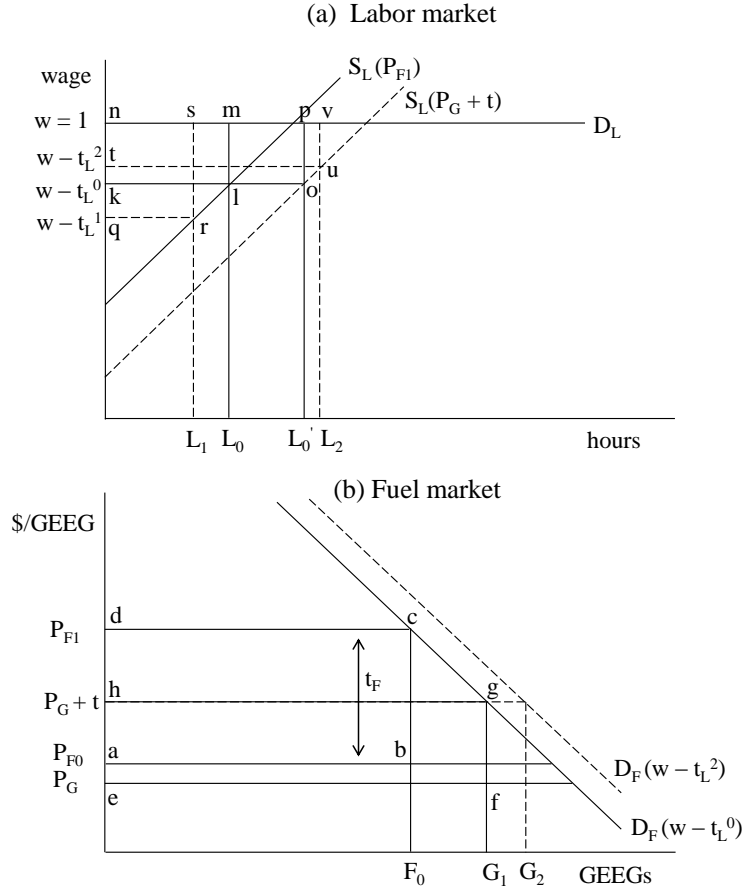
Source: calculated

The primary distortion effect is the most significant component (about 85 percent) of the total welfare change. This reflects in large part the elimination of the RDC due to ‘water’ in the ethanol price premium (\$4 billion). Welfare gains also arise because eliminating the mandate decreases both price and quantity distortions. The fuel price decreases from \$2.31/GEEG to \$2.25/GEEG, and the amount of fuel in energy-equivalent terms increases by 1.10 billion GEEGs (Table A2). In Figure 1, this is depicted as the transition from area *geh* to area *abc*, yielding a reduction in the distortion equal to the difference between the two triangles.

The decrease in the fuel and corn prices after the mandate is removed increases the real wage; this shifts the labor supply curve to the right, as depicted in panel (a) of Figure 2.¹⁹

¹⁹ $S_L(P_{F1})$ denotes labor supply curve when the price of fuel is P_{F1} (i.e., with the mandate), and $S_L(P_G + t)$ denotes the labor supply curve after the mandate has been abandoned. Demand for labor is assumed to be perfectly elastic in Figure 2.

Figure 2. Fiscal Interaction Effects of Removing a Blend Mandate



Keeping the labor tax rate at its original level t_L^0 , rectangle $lop m$ represents a positive tax interaction effect that we estimate to be \$1.54 billion (17 percent of the total welfare change). This effect is positive because the mandate removal causes an expansion of the labor tax base.

Although the quantity of fuel in energy terms increases, its volume measured in gallons actually decreases. This happens because in the absence of the mandate, no ethanol is consumed and the fuel consists exclusively of gasoline. Because gasoline has lower volume than the same energy-equivalent of ethanol, the total volume of fuel decreases. This decrease results in a reduction in the fuel tax revenue because the fuel tax is levied on a volumetric basis. In order to

be able to depict this situation in panel (b) of Figure 2, we have to convert the volumetric fuel tax into its energy-equivalent. Denoting t_F as the common energy-based fuel tax for ethanol and gasoline, it has to satisfy $t_F F = (t/\gamma)E + tG$, from which $t_F = \theta(t/\gamma) + (1-\theta)t$, where F , E , and G , where $F = E + G$, denote quantities of fuel, ethanol, and gasoline, respectively, and $\theta = E / F$ denotes the blend mandate.

The initial fuel tax revenue in panel (b) of Figure 2 corresponds to the rectangle $abcd$. (Price P_{F0} represents a fuel price in the absence of the fuel tax t). When the mandate is removed, the consumer price of fuel falls to $P_G + t$, earning tax revenue of area $efgh$ (area $efgh$ is smaller than area $abcd$). The loss of fuel tax revenue must be compensated by increasing the labor tax to keep the real government transfer to consumers constant. This is depicted in panel (a) of Figure 2, where the increase in the labor tax corresponds to a lower after tax wage $w - t_L^1$ (holding the labor supply curve at its original position). This yields labor tax revenue equal to area $qrsn$ which must be larger than the original revenue of $klmn$. The positive difference between these two areas offsets the revenue loss in the fuel market. Because the labor market distortion has increased, the revenue recycling effect is equal to -\$63 million. The amount of labor L_I is only hypothetical, however, because it assumes no tax-interaction effect (in reality, these effects happen simultaneously).

Our simulation shows that the final labor tax rate decreases from 0.3996 to 0.3983, and labor tax revenue also decreases. In panel (a), this is depicted as a shift up of the after-tax wage: from $w - t_L^0$ to $w - t_L^2$. This happens because the tax interaction effect outweighs the revenue recycling effect. The final labor tax revenue is represented by area $tuvn$, which must be smaller than area $klmn$. Note also that because the real wage rate increases, the demand for fuel (and corn

for non-ethanol use) increases, which is depicted by the demand curve $D_F(w - t_L^2)$ in panel (b).

The final labor tax t_L^2 solves: $t_F F_0 + t_L^0 L_0 = t G_2 + t_L^2 L_2$.

Eliminating the mandate yields a welfare loss of \$173 million from the externality effect.

The welfare losses arise from two sources: the share of the dirtier fuel (gasoline) in the blend increases, and fuel demand increases due to the fuel price decrease.

The main result from Table 2 is that the tax interaction effect of removing the mandate results in a welfare gain of \$1.54 billion which is partially offset by a welfare loss of \$63 million due to the revenue recycling effect. This means the *net* fiscal interaction welfare effect is again significant in magnitude, although the magnitude is not large relative to the primary distortion or total welfare gain.²⁰ The net welfare gain associated with the abolition of the blend mandate is largely due to elimination of the RDC worth \$4 billion.

Welfare Comparison of a Tax Credit and a Mandate

This section is motivated by a recent literature which shows that in a partial equilibrium framework an optimal biofuel mandate is welfare superior to an optimal tax credit not only with a suboptimal fuel tax (de Gorter and Just 2010b), but also without it (Lapan and Moschini, 2012). Because in our model both optimal policies are zero (due to RDC), we do not perform a general equilibrium welfare comparison analogous to the above studies. Instead, we fix the blend mandate at its status quo level (5.88 percent) and calculate a tax credit that by itself would generate an equivalent quantity of ethanol. We then study the welfare effects of removing both policies. To see how the fuel and labor taxes affect the welfare outcome, we consider three cases summarized in Table 3: (i) both taxes exist, (ii) fuel tax only and (iii) labor tax only.

²⁰ Compare this net fiscal interaction gain of \$0.91 billion (= 1.54-0.63) with the welfare loss of \$7.13 billion due to deterioration of the terms of trade in oil imports and corn exports implied for the removal of the binding tax credit in Cui et al. (2011).

Table 3. Welfare Effects of Removing Status Quo Mandate vs. an Equivalent Tax Credit

Pre-Existing Distortion Scenario	Welfare change (\$ billion)	
	Mandate	Tax credit
Fuel tax and labor tax	7.096	6.607
Fuel tax*	6.296	5.693
Labor tax	7.227	7.269

* The value of the government transfer is allowed to freely adjust in these simulations

Source: calculated

Consider first the case where both the fuel and labor taxes are present, and the ethanol quantity under the mandate and tax credit alone is 10.98 billion gallons (Table A3). When each policy is eliminated, ethanol production in both cases falls to zero because the existing ‘water’ prevents any ethanol production without a biofuel policy. Although the decrease in ethanol production is the same for both policies (10.98 billion gallons), the removal of the mandate yields a greater total welfare gain (\$7.096 billion) than the removal of the tax credit (\$6.607 billion). Alternatively, these welfare changes can be interpreted as follows: the introduction of a biofuel mandate reduces welfare by \$7.1 billion, while the introduction of the same quantity of ethanol through a tax credit reduces welfare by only \$6.6 billion. This implies the tax credit is welfare superior to the mandate. But this result needs to be interpreted cautiously.

Because we do not compare optimal policy levels, our finding does not violate the theoretical conclusion of Lapan and Moschini (2012) about the superiority of the mandate. But even when the tax credit and the mandate are compared for the same level of ethanol production, de Gorter and Just (2010b) show theoretically that the mandate welfare dominates the tax credit and more so if both policies are coupled with a suboptimal fuel tax. However, the results presented in the first set of columns in Table 3 are clearly not in line with this prediction.

The explanation is quite simple and intuitive: our fuel tax of \$0.49/gallon is not *suboptimal* (i.e., less than the external cost of the externality of \$0.06/gallon reported in Table A1), but it is *superoptimal*, meaning higher than the marginal external cost.²¹ Because the mandate by itself acts as an implicit tax on fuel consumption (in the form of a higher fuel price), the addition of a superoptimal fuel tax makes it even more distortionary. On the other hand, because the tax credit lowers the fuel price, it works in the opposite direction and brings the effective fuel tax closer to its optimal level.

This explanation also holds for the case when only the fuel tax is present, as seen in the second row of Table 3. However, as shown in the third row, the mandate becomes superior to a tax credit in the absence of the fuel tax (with only the labor tax in place). This is consistent with the explanation above as well as the prediction of de Gorter and Just (2010b) because the (zero) fuel tax is suboptimal. In this scenario, when the mandate implicitly taxes gasoline consumption to pay for higher ethanol prices, it is beneficially compensating for the suboptimal fuel tax.

To test the impact of RDC on the results in Table 3, we artificially increase the gasoline price (to \$2.41/gallon) such that ‘water’ in the ethanol price premium is eliminated. The welfare gains from removing the policies given this assumption are reported in Table 4. The welfare gains are significantly smaller than their counterparts in Table 3, largely because the RDC of \$4 billion is now absent. However, the results in Table 4 are qualitatively unchanged from Table 3, so we conclude that the presence of ‘water’ has no qualitative impact on the welfare superiority of a tax credit over a mandate (for the same ethanol production) under a superoptimal fuel tax.

²¹ Like us, Cui et al. (2011) also consider only one externality – carbon (CO₂) emissions. They assume a marginal emissions damage of \$20/tCO₂. Parry et al. (2007) assume the marginal external damage due to carbon emissions to be \$25/tCO₂, which corresponds to \$0.06/gallon. Therefore, the marginal emissions damage of \$20/tCO₂ in Cui et al. (2011) translates into \$0.048/gallon which is less than the fuel tax of \$0.39/gallon they use. Hence, their fuel tax is superoptimal.

Table 4. Welfare Effects of Removing Status Quo Mandate vs. an Equivalent Tax Credit: the 'No Water' Case

Pre-Existing Distortion Scenario	Welfare change (\$ billion)	
	Mandate	Tax credit
Fuel tax and labor tax	1.507	1.381
Fuel tax*	0.506	0.300
Labor tax	1.035	1.045

* The value of the government transfer is allowed to freely adjust in these simulations

Source: calculated

The central message of the analysis above is that in countries which have a superoptimal fuel tax, like Great Britain (Parry and Small 2005), a tax credit will be welfare superior to a mandate when comparison is made for the same ethanol production.

1.7 Conclusion

Although several earlier works have studied the welfare effects of the U.S. biofuel policies, the analyses have primarily been done in a partial equilibrium framework, thus failing to capture general equilibrium fiscal interaction effects of biofuel policies. In this essay, we build a tractable general equilibrium model of the U.S. economy to analyze the welfare effects of a change in (or a complete removal of) the U.S. biofuel policies, a tax credit and a blend mandate. More specifically, we assume the government keeps the real transfer to consumers fixed and adjusts the labor tax whenever a change in a biofuel policy occurs. This enables us to study two interactions of biofuel policies with the broader fiscal system.

First, the tax interaction effect arises when the price of corn or fuel increases (decreases) as a result of a biofuel policy change, making the real wage decrease (increase) and thus contracting (expanding) the labor supply curve. The ensuing loss (gain) in labor tax revenue – holding the labor tax constant – represents the tax interaction effect. Second, a change in the biofuel policy affects the government fuel tax receipts. If the biofuel policy change yields greater

(lesser) fuel tax revenue, this additional revenue is used to reduce (increase) the pre-existing labor tax to keep the real transfer to the consumer fixed; depending on the change in the labor tax, the pre-existing distortion in the labor market can either increase or decrease. The direction of the net fiscal interaction effect depends on the direction and magnitude of its tax interaction and revenue recycling components.

To mirror the recent expiration of the U.S. corn-ethanol tax credit, we simulate the welfare effects of removing the tax credit, keeping the blend mandate unchanged. Eliminating the tax credit yields a small gain in total welfare of \$9 billion, but the fiscal interaction effects are more pronounced. Because the fuel price increases when the tax credit is removed, the tax interaction effect is estimated to be a loss of \$63 million. But because the fiscal savings due to the absence of the tax credit can be used to reduce the labor tax, the revenue recycling effect of this policy change is a welfare gain of \$360 billion. This implies that the *net* fiscal interaction welfare effect is large compared to the total welfare change, and it is approximately equal to the welfare loss of the primary distortion effect.

Motivated by our finding that the optimal mandate (as well as the tax credit) is zero, we analyze the welfare effects of the elimination of the status quo mandate. We indeed find that the current blend mandate is not optimal as its abandonment results in a total welfare gain of more than \$8 billion. Significant welfare gains come from the elimination of the RDC (estimated to be \$4 billion), as well as from a positive tax interaction effect of \$1.54 billion. However, the welfare gains from the tax interaction effect are partially offset by a loss of \$63 million due to the revenue recycling effect. In sum, the *net* fiscal interaction welfare effect of removing the mandate is significant in magnitude, although the magnitude is smaller relative to the primary distortion or total welfare gain.

For the same ethanol production, a blenders' tax credit is empirically found to be welfare superior to a mandate. This ordering is found to hold regardless of the presence of 'water' in the ethanol price premium (i.e., the gap between the free market ethanol price and the intercept of the ethanol supply curve). This is a novel result, since previous literature has concluded that, given the same ethanol production, a mandate always welfare dominates the tax credit. This finding is driven by the fact that the fuel tax is superoptimal in our model (i.e., it exceeds the marginal external cost of gasoline consumption). The superoptimality of the fuel tax in our model reflects the exclusion of vehicle-miles-traveled externalities such as traffic accidents or congestion. The implication of our results is that the biofuel mandate is likely to be inferior to a blenders' tax credit (or a tax exemption) in countries that have superoptimal fuel tax, such as the United Kingdom (Parry and Small 2005).

CHAPTER 2

TRADING QUALITY AND NEWNESS: INCOME SIGNALING AND THE CONSUMPTION OF DURABLE VISIBLE GOODS

2.1 Introduction

In this essay I theoretically and empirically study consumer behavior in a durable good market where consumption can be used as a “status signal.” The signaling-by-consuming framework consists of three basic assumptions: (1) consumers derive utility from status, a non-market good which would be allocated according to income if income were observable; (2) in fact, income is not observable; (3) hence, consumers face a trade-off between visible goods which could be used to signal income and non-visible consumption which has only intrinsic value. In this framework, a signaling equilibrium can arise where high-income consumers use “conspicuous consumption” of certain visible goods to distinguish themselves and increase their status. The similarity between this model of conspicuous consumption and other signaling models is noted by Spence (1973).

I begin by extending a classic model of income signaling with a visible good (Ireland 1994) to reflect the consumption of a durable good stock that is characterized by three attributes: quality, newness, and stock size. Any of the stock attributes could be used to increase expenditure and signal income—consumers could buy higher-quality items that cost more, they could replace their items more quickly, or they could own more items at once. I show theoretically how the newness or quality of a durable good stock could be used as a status signal in a signaling equilibrium. The empirical implication of the model is that the income elasticities of demand for attributes of a durable good stock can be affected by the visibility of the durable good, and visibility has a greater effect on the income elasticity of the attribute that is used to signal status. For example, if newness is the status signal, the income elasticity of newness is

distorted upward relative to its counterpart when the durable good is not visible. Which attribute of the durable good stock is actually used as a status signal (if in fact status signaling exists), is an empirical question. Although we cannot observe which attribute is used as the status signal, the effect of the durable good's visibility on the attributes' income elasticities can provide suggestive evidence. For example, a positive effect of visibility on an attribute's income elasticity is theoretically consistent with the presence of status signaling in that attribute.

The apparel category of goods presents an ideal opportunity to quasi-experimentally vary the level of durable good visibility and measure its effect on the income elasticity of demand for stock attributes. I use Consumer Expenditure Survey data on the consumption of a visible apparel good (shirts) and a non-visible apparel good (underwear) to estimate the income elasticities of quality, as measured by average item price, and quantity, as measured by items purchased per quarter. The quantity variable reflects both average item age and stock size, so these data do not enable me to disentangle the effect of visibility on demand for newness from its effect on demand for stock size.

I estimate separate income elasticities by apparel category, so the difference between category elasticities for a given variable reflects a visibility-based distortion that could reflect a signaling equilibrium based on that variable. I compute a difference-in-differences type of statistic which compares the difference in quantity attributable to visibility to the difference in quality attributable to visibility. My central empirical finding is that visibility is associated with an approximately three-fold increase in the elasticity of quantity with respect to income, but visibility does not significantly increase the elasticity of quality with respect to income. This suggests that quantity is more likely than quality to be a status signal, if status-seeking preferences exist and apparel is used to signal income.

My theoretical result that durable good newness could be used as a status signal could help explain an intriguing feature of many durable goods markets: consumers often replace a good they already own with another good of equal functional value. For example, a homeowner may redecorate her living room by changing the color of her curtains, or an apparel consumer may replace his necktie with a necktie of a different width. Replacement decisions such as these, which are not made for any observable functional reason, are the essence of “fashion.” Since replacement is costly, buying new goods for newness’s sake could actually form the basis of an equilibrium where consumers use “fashion” to signal income. Preference for variety or other taste-based explanations could also rationalize costly replacement without functional change, but unless these preferences applied differentially to visible and non-visible goods it could not explain my results. My empirical results are consistent with the existence of status signaling in apparel quantity, which would result if the newness and/or size of consumers’ apparel stocks were a status signal.

The rest of this chapter is organized as follows. Section 2.2 reviews previous literature related to this essay and suggests some of its similarities with and differences from this essay. In section 2.3, I extend a classic model of status-seeking income signaling to incorporate “visible newness,” which is an important feature of durable goods consumption. In section 2.4, I introduce the dataset of apparel purchases from the Consumer Expenditure Survey. In section 2.5, I describe my empirical models for estimating the income elasticities of quality and quantity and for testing the effect of visibility on the income elasticities. Section 2.6 presents empirical results. Section 2.7 discusses my results and concludes the chapter.

2.2 Related Literature

This essay is most closely related to the signaling literature which explains phenomena of visible consumption by status-seeking motives. The model described in section 2.3 is based on Ireland (1994), and it is similar to that of Glazer and Konrad (1996). Glazer and Konrad (1996) and Ireland (1994) present models where consumers of different income types allocate their income between a non-visible good and a visible good (in the case of Ireland) or service (charitable giving, in the case of Glazer and Konrad). It is assumed that consumers derive intrinsic utility from consuming both, and they also derive utility from status. Status is a function of income or wealth, but visible good consumption is the only variable that is observable for the purpose of status allocation. In both of these models, the single-crossing property is satisfied, and in the separating equilibrium that results, wealthier consumers face a lower marginal cost of over-consuming the visible good so they are able to separate themselves. In effect, the status-signaling game causes high-type consumers to distort their consumption towards the visible good relative to a no-signaling equilibrium. Glazer and Konrad (1996) show that visible expenditures increase with income at a convex rate unless status is more concave than the intrinsic parts of utility.

Other authors have modeled this type of status-seeking as a zero-sum game. Frank (1985) defines “positional goods” as those for which consumers have extrinsic utility that is increasing in their percentile ranking of consumption. Goods which are not observable are inherently non-positional in this framework. Coelho and McClure (2007) use a zero-sum model for fashion goods in particular; they assume that consumers’ value of a fashion depends on others’ stock, and fashion goods have a zero-sum nature since social distinction is in limited availability. Like my theoretical model, their model of visible durable good consumption is tied

to change; they assert that if fashion did not change and a second-hand market existed, everyone would be ‘fashionable,’ which would negate the value of fashion as a signal. They allude to the importance of replacement costs for the formation of a signaling equilibrium, adding in a footnote, “As long as tie styles... continually change, the cost of consistently wearing a fashionable tie is higher for the poor than for the wealthy” (p. 600). This is similar in spirit to the result I find in section 2.3, where the newness of a durable good stock is shown to be a possible variable for the basis of a signaling equilibrium.

This essay also relates to a theoretical body of literature which tries to derive features of fashion markets using extended rational expectations models. Two features of fashion markets which do not arise from standard formulations of preferences are fashion cycles (the costly change of style for no functional purpose), and “Veblen effects,” which Bagwell and Bernheim (1996) describe as “consumers exhibit(ing) a willingness to pay a higher price for a functionally equivalent good.” For example, Caulkins et al. (2007) build a model which exhibits fashion cycles by assuming that consumers have an innate preference for fashion and the fashion-good producer faces a low-cost imitator. They identify an equilibrium where the innovative producer infinitely cycles through product space.

Pesendorfer (1995) also builds a model which yields fashion cycles in equilibrium. He assumes that fashion is inherently non-functional, rather than innately valuable, but fashion serves a functional purpose in equilibrium by allowing societal strata to differentiate themselves. The consumption externality associated with fashion arises endogenously as consumers compete in a “dating game” where fashion consumption can serve as a signal of type. In Pesendorfer’s model, a monopolist designer faces a fixed cost of (re)-design but cannot commit to a high price; for a given style, price falls over time more and more “low” types buy it. A tipping point exists

where it becomes optimal for the monopolist to introduce a new style whose price can extract the full value of a perfect signal. The equilibrium of the game is fashion cycles with fixed length, where the length depends positively on the fixed cost of design. The model has an appealing similarity to reality because it displays both snob effects and bandwagon effects, depending on the stage of the fashion cycle. My model and that of Pesendorfer (1995) both imply that income signaling can lead to demand for durable good replacement that is faster than replacement without income signaling; I abstract from modeling a specific evolution of style and only assume that the good's "usedness" is visible through some unspecified means.

Bagwell and Bernheim (1996) thoroughly analyze the possibility of Veblen effects in a signaling model in a general equilibrium framework. They consider a larger set of consumer choices for signaling; for the visible good, consumers are assumed to choose (i) brand, (ii) quantity, (iii) quality (from among the quality levels offered by firms), and (iv) they can also can signal income by paying a higher price for equal quality, which is a true "Veblen effect." In the Bagwell and Bernheim model, Veblen effects do not arise under the standard "single-crossing assumption" about preferences across types unless quantity and quality are both fixed. They point out that this is the same intuitive result as in Pesendorfer (1995). If only quality is allowed to vary in the single-crossing framework, high-types distort their quality decision rather than pay more for an equivalent good, but if both quantity and quality are allowed to vary, high-type households differentiate themselves by conspicuous good quantity. This outcome arises despite quality and quantity being perfect substitutes in utility.

Bagwell and Bernheim (1996) do find that Veblen effects exist when preferences satisfy a certain tangency property²²; the tangency property yields an equilibrium where luxury and

²² This property requires that the indifference curves of high- and low-type consumers in the quantity-expenditure plane are tangent at exactly one point. See Figure 2 in Bagwell and Bernheim (1996) for an illustration.

budget brands co-exist and offer equal quality, yet luxury brands maintain a price above marginal cost which the high-types are willing to pay in order to differentiate themselves. In this equilibrium, signaling distorts the price and quantity choices of high-type households but not their quality choice. If preferences exhibit the tangency property, Veblen effects also exist if quantity is fixed or quantity and quality are both fixed. In my model, prices are determined by production in perfect competition and I assume that the single-crossing property holds, so we would not anticipate the existence of Veblen effects even if branded goods existed. More directly, Veblen effects are not possible in my model since consumers do not choose the price of the visible durable good separately from its quality.

The welfare analysis of signaling models mostly concludes that signaling is wasteful. For example, fashion cycles are wasteful in Pesendorfer's model, because everyone would be better off if there were only one design and the monopolist could commit to a high price for it. In the zero-sum models, excess spending on the positional good also results in welfare losses (Frank 2005). However, the distortions caused by signaling models can have interesting implications for the welfare cost of taxes. In the Ireland (1994) model, a tax can be Pareto-improving, and a non-distortionary tax on the luxury good is feasible in the Bagwell and Bernheim (1996) model with Veblen effects. I do not study welfare effects directly, but my model's basis on Ireland (1994) suggests that a tax on the visible attribute(s) of a durable good could be welfare-improving, if such a tax could be implemented.

This essay also contributes to an empirical literature about conspicuous consumption. Consumer Expenditure Survey data are commonly analyzed in this literature. An exception is Christen and Morgan (2005), who use national U.S. data from 1980-2003 to show that income inequality is positively correlated with the level of household debt relative to income. They

propose that a theory of conspicuous consumption could explain their evidence that the growing real wage gap between richer and poorer led to greater relative spending by the poor.

Heffetz (2011) studies the relationship between category visibility and income elasticity using the Ireland (1994) model. He shows theoretically how the existence of income signaling with a visible good and a non-visible causes an upward distortion in the income elasticity of demand for the visible good and a corresponding downward distortion in the income elasticity for the non-visible good. After conducting a survey to determine the visibility level of 31 categories of goods and services in the Consumer Expenditure Survey, he finds that visibility explains up to one-third of the cross-category variation in total expenditure elasticity with respect to income. My empirical results in section 2.6 are consistent with his model's prediction that total expenditure elasticity with respect to income is greater for more visible goods.

Charles et al. (2009) use Consumer Expenditure Survey data from 1986 to 2002 to study the relationship between conspicuous consumption and race. They demonstrate that black and Hispanic consumers devote more of their income to conspicuous consumption than whites in terms of expenditure share, but differences in average income across race-state groups explain most of this difference. Their theoretical framework from Glazer and Konrad (1996) implies that if poorer people are added to the reference group, visible spending increases at all income levels in the group. Their empirical findings match this prediction; they find that the expenditure share of conspicuous goods is decreasing in the average reference group income, where the reference group is defined at the race-state level.

Bils and Klenow (2001) do not address the question of category visibility, but they conduct an empirical analysis similar to section 2.4 of this essay. They study the relationship between product quality and income using the U.S. Consumer Expenditure Survey from 1980-

1996, and their central focus is on quality growth as incomes increase over time. For 66 categories of durable goods, they estimate the “quality Engel curve”- the relationship between the unit price that a consumer pays for a given category of goods and total non-durable consumption. They find that jewelry, window coverings, rugs, and cars exhibit the steepest quality Engel curves, where a 1% increase in non-durable expenditure is associated with a 1% increase in purchase price. The shallowest quality Engel curves, for categories including microwave ovens, vacuums, sewing machines, and lawn and garden equipment, reflect elasticities of 0.25% or less. At a glance, the goods with steep Engel curves seem to be more visible than those with shallower curves, and this aligns well with the findings of Heffetz (2011) and my results in section 2.6.

Bils and Klenow (2001) also estimate quantity Engel curve slopes and compare the magnitude of the quantity slope to the sum of the quantity and quality slopes. My empirical method for estimating the slopes of the Engel curves is slightly different from theirs, but this is qualitatively the same analysis I perform in section 2.6. Their category list includes 13 categories of apparel goods and three categories of footwear, but they do not have a category for non-visible apparel consumption (underwear). They find that the quality Engel curve is flatter than average for all apparel categories (indicating that quantity demand grows faster than quality demand as income increases) and steeper than average for the footwear categories. For both the visible and non-visible apparel category in my more recent CEX data sample, I similarly find that the elasticity of number of items with respect to income is larger than the elasticity of average item price with respect to income. By comparing a visible category to a non-visible category, I can quasi-experimentally measure the effect of visibility on this difference between quantity and quality.

2.3 Theoretical Model

Consumers derive utility from two market goods, a consumable good x that is not visible to observers and a durable good V that may be visible. Consumers may also derive utility from status, a non-market good. I assume that consumers may own multiple units of the durable good, and each consumer's durable good stock is characterized by three variables: (i) the number of items in the stock at any point in time (W), (ii) the quality level of items in the stock (Q), and (iii) the “newness” of the stock, as captured inversely by the average age of the items in the stock (A). Per-period utility from the visible durable good depends on each of the stock's properties; the consumer chooses a consumption plan (A, Q, W) for the stock, and I consider a steady state where the stock attributes are constant. I assume that there is no trade in second-hand goods if consumers replace items which are otherwise still serviceable, and the consumable good is assumed to be homogenous. Let $f(A, Q, W, x)$ denote the consumer's intrinsic per-period utility from the two market goods, where f is decreasing in A (since age is a “bad” which represents the opposite of newness) and increasing in the other variables. If the durable good is not visible, the consumer maximizes f .²³

Consumers have income y which defines their type, and income is distributed on the interval $[y, \bar{y}]$. The status good is allocated by observers who would like to allocate greater status to consumers with higher income but cannot observe income directly. If the durable good is visible, the observers infer consumers' income from their durable good consumption. Bagwell

²³ In this model, consumers derive utility from the physical age of a durable good instead of an “effective age” that captures wear and tear. In reality, both factors matter for consumers' replacement decisions. This assumption causes me to ignore the possibility that stock size has a mitigating effect on the utility that is gained from newness. With a larger stock, it is plausible that each item would be used less, so the average “effective age” of the stock relative to its average physical age would be relatively low. However, the focus on physical age is arguably appropriate for the apparel setting. Physical age can serve as a reasonable proxy for effective age, and physical age can also capture replacement for newness's sake alone, which is the essence of “fashion.” The quote in the Introduction indicates that the phenomenon of replacement for the purpose of some visible signal such as fashion, rather than replacement due to wear and tear, has existed for some time. Morgan and Birtwhistle (2009) find more recent evidence for this phenomenon in their study of the disposal of fashion apparel by young consumers.

and Bernheim (1996), Pesendorfer (1995), Glazer and Konrad (1996), Ireland (1994), and other theoretical models share this similar structure for status: it is allocated to consumers by social contacts according to their belief about the consumer's total wealth, which must be inferred by observing visible consumption alone. From this point, I use Ireland's model of status signaling to show how an attribute of the durable good can be used as a signal of income by high-type consumers, if the durable good is visible.

Following Ireland (1994), I assume that the consumer's total utility can be expressed as a weighted sum of intrinsic utility, $f(A, Q, W, x)$, and the observer's inference of the consumer's intrinsic utility. (Note that a correct inference of the consumer's intrinsic utility is equivalent to a correct inference of his income, since consumers differ only in income.) As noted above, any attribute of the durable good stock could be used to increase expenditure (and hence signal status), if the durable good is visible. Without loss of generality, let $D_v \in \{A, Q, W\}$ denote the attribute that is actually used as the status signal²⁴. Let a denote the relative weight on status, and let $g(D_v)$ denote the inference function which maps the level of the status signal attribute to non-visible consumption x . The consumer's total utility is:

$$U(A, Q, W, x) = (1 - a)f(A, Q, W, x) + af(A, Q, W, g(D_v)). \quad (1)$$

The price level of the durable good is given by z , and the consumable good is taken as the numeraire. Let $s(A, Q, W)$ denote the consumer's per-period expenditure on the durable good stock. Given a constant stock size W and average age A , the number of items which will be purchased in each period is equal to $W/(2A - 1)$. I assume that the cost of quality Q is equal to $c(Q)$. Following Bils and Klenow (2001), I assume that $c(Q)$ reflects the production cost associated with quality, where prices are set in perfect competition. Hence, total expenditure on

²⁴ Equilibria could also exist where more than one visible good attribute is used to signal income, but for simplicity I have restricted my analysis to the case of one-dimensional signaling.

the visible good in each period is given by $s(A, Q, W) = zc(Q)W/(2A - 1)$. The per-period budget constraint can be written as:

$$y = x + s(A, Q, W). \quad (2)$$

Plugging the budget constraint (2) into the utility function (1) yields the consumer's optimization problem:

$$\max_{A, Q, W} U(A, Q, W) = (1-a)f(A, Q, W, y - s(A, Q, W)) + af(A, Q, W, g(D_V)). \quad (3)$$

In a separating equilibrium with $a > 0$ and the visible status signal D_V , the numeraire quantity x is equal to $g(D_V)$ for each income type, and every consumer's type is correctly inferred. Ireland (1994) uses reasoning similar to Mailath (1987) to prove the existence of a separating equilibrium in this model under certain conditions, and these conditions are met for the functional form assumed in the model analysis below.²⁵ As in other signaling models such as Spence (1973), the separating equilibrium arises from preferences satisfying a “single-crossing” assumption. In a separating equilibrium, the lowest type has no incentive to distort her consumption, since she will be correctly identified as the lowest type in equilibrium, but all higher income types distort their consumption towards the signaling variable just enough to distinguish themselves from the next-lowest type. This is made possible by the single-crossing assumption, which means that distortion toward the signaling variable grows more costly as income decreases.

The remainder of this section considers a specific, tractable functional form for the intrinsic utility function. I first summarize the equilibrium that results if the durable good is not visible, which is equivalent to solving for the equilibrium when $a = 0$. If the durable good stock

²⁵ Ireland (1994) shows that the equilibrium exists for a differentiable function $g(V)$ and does not consider equilibria which could arise from other types of inference functions; I follow his approach.

is not visible, it cannot be used to signal status and its attributes will be chosen to maximize intrinsic utility alone. When neither good is visible, the observers' allocation of status must be independent of any action taken by the consumer, so status is exogenous from the consumer's perspective. Next, I derive two equilibria that can result if $a > 0$ and the durable good is visible: I consider the equilibrium if $D_v = A$ and the equilibrium if $D_v = Q$. My analysis of these equilibria shows that using D_v as a status signal results in its elasticity of demand with respect to income being larger than its counterpart when $a = 0$.

Assume that utility is linearly separable in the durable good attributes and numeraire quantity and that the price of quality is an exponential function:

$$U(A, Q, W, x) = -\beta_A \ln A + \beta_Q \ln Q + \beta_W \ln W + \beta_x \ln x; \\ c(Q) = \delta_1 e^{\delta_2 Q}. \quad (4)$$

The derivatives of this function satisfy the conditions outlined by Ireland (1994), such that if $a > 0$ there exists a separating equilibrium where the signaling variable D_v is used to signal the numeraire good consumption associated with a given income type.²⁶ My solution for solving the model in the $a > 0$ equilibria makes use of the solution approach in Heffetz (2011), who also uses the Ireland (1994) model. Derivations for the three equilibria are found in Appendix 7.

2.3.1 Non-visible durable good ($a = 0$)

If $a = 0$, the solution to the consumer's problem in equation (3) given the functional form assumptions in (4) has the following demands for the durable good attributes A , Q , and W :

²⁶ These conditions are: $f_{D_v} > 0$; $f_x > 0$; $f_{D_v D_v} \leq 0$; $f_{xx} < 0$; $f_{D_v x} \geq 0$. In the case of $D_v = A$, f is decreasing in A so the signaling function will have a negative derivative.

$$\begin{aligned}
A &= \frac{\beta_A}{2(\beta_A - \beta_W)}; \\
Q &= \frac{\beta_Q}{\delta_2 \beta_W}; \\
W &= y \frac{\beta_W^2}{z(\beta_x + \beta_W)(\beta_A - \beta_W) \delta_1 \exp\left(\frac{\beta_Q}{\beta_W}\right)}.
\end{aligned} \tag{5}$$

I assume that $\beta_A > \beta_W$ so that A and W are defined and greater than zero. If the durable good is not visible, the elasticity of quality with respect to income and the elasticity of newness with respect to income are both zero, since newness and quality do not vary with income given the functional form assumption for utility. The elasticity of stock size with respect to income is equal to one.

2.3.2 Visible durable good with newness as status signal ($a > 0, D_V = A$)

If $a > 0$ and A is the variable which forms the basis for the signaling equilibrium, consumer demand for the durable good attributes satisfies the following equations:

$$\begin{aligned}
A : \frac{y}{C} (1 - zc(Q)\Delta) &= (2A - 1)^{-\frac{\beta_W}{a\beta_x}} A^{\frac{\beta_A}{a\beta_x}}, \\
W &= y(2A - 1)\Delta, \\
\text{and } Q &= \frac{\beta_Q}{\delta_2 \beta_W}, \\
\text{where } \Delta &\equiv \beta_W \left(z((1 - a)\beta_x c(Q) + \beta_W) \right)^{-1}.
\end{aligned} \tag{6}$$

Optimal newness A is defined implicitly by the first equation above, where C is a constant term that reflects the actions of the lowest-income consumer (see Appendix 7 for further details). The level of quality in this equilibrium will be the same as the level that results in (5) when the durable good is not visible, and the elasticity of quality with respect to income will also be zero in this equilibrium.

Although an explicit expression for A is not derived due to non-linearities, we can totally differentiate the implicit equation that defines A to obtain explicit expressions for the elasticities of A and W with respect to income y . These elasticities are:

$$\begin{aligned}\varepsilon_{Ay} &= a\beta_x \left(\frac{2A-1}{2A(\beta_A - \beta_W) - \beta_A} \right); \\ \varepsilon_{Wy} &= \frac{A}{W} 2\Delta \varepsilon_{Ay} + \frac{1}{\Delta}.\end{aligned}\tag{7}$$

The magnitude of the elasticity of A with respect to income is clearly increased relative to the equilibrium when $a = 0$. The elasticity of W with respect to income may be larger or smaller than in the $a = 0$ equilibrium, since the consumer's willingness to substitute A for W depends on their respective levels as well as the price and preference parameters.

2.3.3 Visible durable good with quality as status signal ($a > 0, D_V = Q$)

If $a > 0$ and Q is the variable which forms the basis for the signaling equilibrium, consumer demand for the durable goods attributes satisfies the following equations:

$$\begin{aligned}A &= \frac{\beta_A}{2(\beta_A - \beta_W)}, \\ Q: \frac{y}{B} (1 - zc(Q)\Delta) &= Q^{\frac{\beta_Q}{a\beta_x}} \exp\left(Q \frac{\beta_W \delta_2}{a\beta_x}\right), \\ \text{and } W &= y\Delta \left(\frac{\beta_W}{\beta_A - \beta_W} \right), \\ \text{where } \Delta &\equiv \beta_W \left(z((1-a)\beta_x c(Q) + \beta_W) \right)^{-1}.\end{aligned}\tag{8}$$

Optimal newness A in this equilibrium is the same as its counterpart in (5) when the durable good is not visible, and the elasticity of demand for newness with respect to income is also zero. Optimal quality Q is defined implicitly by the second equation above, where B is a constant term that reflects the actions of the lowest-income consumer (see Appendix 7 for further details).

As in the $D_V = A$ equilibrium, we can totally differentiate the implicit equations that define Q and W to obtain explicit expressions for their elasticities with respect to income. These elasticities are:

$$\varepsilon_{Qy} = \left(\frac{\beta_Q}{a\beta_x} + Q \frac{\beta_W \delta_2}{a\beta_x} - Q \beta_W^2 c'(Q) \frac{(1-a)\beta_x \beta_W c(Q) - \Delta z}{\Delta z (\Delta z - \beta_W^2 c(Q))} \right)^{-1},$$

$$\text{and } \varepsilon_{Wy} = \frac{y}{W} \left(\frac{\beta_W^2}{\beta_A - \beta_W} \right) - Q \delta_2 \frac{(1-a)\beta_x \beta_W z c(Q)}{\Delta} \varepsilon_{Qy}. \quad (9)$$

The magnitude of the elasticity of Q with respect to income is greater than its counterpart when $a = 0$. The elasticity of W with respect to income may be larger or smaller than in the $a = 0$ equilibrium, depending on the consumer's preference parameters.

2.3.4 Summary

In each of the equilibria, demand for newness, quality, and stock size can be expressed as implicit functions of income, preference for status a , the lowest income, preference parameters denoted by $\boldsymbol{\beta} = (\beta_A, \beta_Q, \beta_W, \beta_x)$, and the price vector denoted by $\mathbf{P} = (\delta_1, \delta_2, z)$:

$$A = A(y, a, \underline{y}, \boldsymbol{\beta}, \mathbf{P}),$$

$$Q = Q(y, a, \underline{y}, \boldsymbol{\beta}, \mathbf{P}),$$

$$\text{and } W = W(y, a, \underline{y}, \boldsymbol{\beta}, \mathbf{P}). \quad (10)$$

Demand for the durable good attributes depends on whether or not the durable good is visible as well as which attribute is used as the status signal. Table 5 summarizes the elasticities of A , Q , and W with respect to income y in the three possible equilibria outlined above. Given the functional forms assumed here for intrinsic utility and price of quality, these results demonstrate how the income elasticity of a durable good attribute is larger when the durable good is visible and that attribute is used as a status signal than when the durable good is not visible.

Table 5: Summary of Income Elasticities from Theoretical Model Equilibria

	Not visible $(a = 0)$	Visible with newness as status signal $(a > 0, D_V = A)$	Visible with quality as status signal $(a > 0, D_V = Q)$
ε_{Ay}	0	$a\beta_x \left(\frac{2A-1}{2A(\beta_A - \beta_W) - \beta_A} \right)$	0
ε_{Qy}	0	0	$a\beta_x \left(\beta_Q + Q \left(\beta_W \delta_2 + \left(\frac{ac'(Q)}{\Delta z} \right) \frac{(1-a)\beta_x^2 \beta_W c(Q) - \Delta z}{c(Q) - \Delta z \beta_W^{-2}} \right) \right)^{-1}$
ε_{Wy}	1	$\frac{A}{W} 2\Delta \varepsilon_{Ay} + \frac{1}{\Delta}$	$\frac{y}{W} \left(\frac{\beta_W^2}{\beta_A - \beta_W} \right) - Q\delta_2 \frac{(1-a)\beta_x \beta_W z c(Q)}{\Delta} \varepsilon_{Qy}$

$$\Delta \equiv \beta_W \left(z((1-a)\beta_x c(Q) + \beta_W) \right)^{-1}$$

If the durable good is visible, which equilibrium results depends on the utility function parameters and relative prices. Bagwell and Bernheim (1996) also note that the signaling variable preferred by high-income types depends on the utility specification (footnote 20, p. 358). High-income types will choose the status signal which results in the least costly distortion. Also, although this model has assumed that all attributes of the durable good stock are equally visible if the durable good itself is visible, some alternate assumptions are discussed in section 2.7. Overall, the question of how visibility actually affects the relationship between income and consumption decisions is an empirical question. In section 2.5, I describe an empirical application of this model which can be used to test the effect of durable good visibility on the elasticities of demand for durable good stock attributes with respect to income.

2.4 Data

To isolate the effect of visibility on durable goods consumption, it would be ideal to exogenously vary durable goods' visibility. I consider a quasi-experimental shift in visibility by comparing two categories of apparel goods that differ in visibility but have minimal differences

in functionality: shirts and underwear. The apparel category is an ideal framework for attempting to isolate the effect of visibility on consumption decisions since its visible sub-categories such as shirts are highly visible. According to the survey that Heffetz (2011) conducted to determine the visibility level of categories in the Consumer Expenditure Survey, the most visible categories of consumption are cigarettes and automobiles, followed closely by clothes²⁷. Charles et al. (2009) also use a survey to identify categories of goods that are likely to be used for conspicuous consumption, and they identify three categories which are highly visible and “portable”: clothing/jewelry, personal care, and automobiles. In addition to making these “most visible” lists, the apparel category is often cited in theoretical studies of conspicuous consumption (Bagwell and Bernheim 1996, Pesendorfer 1995, Ireland 1994).

The data for my analysis come from the 2004 – 2010 U.S. Consumer Expenditure Survey (CEX). The two components of the CEX, the Interview survey and the Diary survey, are administered on a rolling basis by the Bureau of Labor Statistics (BLS) to study the consumption habits of a nationally representative sample of consumers. Consumers are defined by “units” which include all members of a household who make joint expenditure decisions.²⁸ From this point on, I refer to a consumer unit as a single “consumer.” The relevant survey for studying durable goods consumption is the Interview survey. Consumers in the sample are interviewed quarterly for four quarters; during each interview they report consumption of various categories of goods for each of the three preceding months. Demographic data are also collected for each consumer.²⁹

²⁷ The category description is, “Clothing and shoes, not including underwear, undergarments, and nightwear.”

²⁸ Three types of consumer units exist: (i) all members of a household who are related in some way (by blood, marriage, adoption, etc.), (ii) individuals who are financially independent, whether they live alone or with others, and (iii) two or more people who live together and make joint expenditure decisions in two or more of the major expense categories (food, housing, and other living expenses) (CEX Glossary, BLS website).

²⁹ Each consumer unit is also associated with a sampling weight which reflects how many consumer units in the total U.S. population it represents. In my analysis, each consumer unit is weighted equally.

My analysis utilizes the expenditure file for the apparel category of consumption. The expenditure file contains the consumers' most detailed level of reporting: number of items purchased and total expenditure at the sub-category level, by month. The dataset for analysis is built by summing observed item quantities and expenditures to the consumer-interview-category level³⁰. Although each observation reflects three months of expenditure data, the data are not at a "quarterly" level (with respect to a calendar date) since the consumers complete the survey in different calendar months. Average item price is calculated as the sum of expenditures divided by the sum of quantities.

My sample includes consumer units whose reference consumer is between the ages of 18 and 65, which results in 62,868 consumer units across all years.³¹ On average, I observe each consumer for 2.78 interviews; 42.4% of consumers are observed for a full four interviews. To measure consumer income, I use the BLS-imputed value of before-tax consumer unit income. This income variable estimates the combined income from all sources (including the value of transfers) for the consumer unit during the 12 months preceding the interview. Income reporting in CEX data has historically been far from complete, and researchers using these data have often relied on total expenditure variables as a proxy for income (Charles et al. 2009, Bils and Klenow 2001). Since 2004, the BLS has provided estimates of consumer unit income using multiple imputation³², and this method results in income estimates which more closely match income in

³⁰ Alternately, I could average across consumer reporting periods, which could decrease measurement error (Charles et al. 2009). However, the BLS imputes income at the interview level (see footnote below for more details), so averaging income across imputations would distort my standard error estimates.

³¹ The full sample contains 63,614 consumers. The observations excluded from my dataset have zero or less income (763 observations), an invalid record for Race (410 consumers, 1299 observations) or Education (226 consumers, 723 observations), or outlier Underwear quantity in the top 0.5% of observations (59 observations). The outlier Underwear item counts range from 216 to 1752, and their average income is not statistically different from the average income of the sample, so I assume these are transcription errors occurring at random.

³² The BLS uses a standard regression-based method for imputing missing income data. The non-missing data are used to estimate regression coefficients which relate income to other reported variables, and then the missing data values are estimated using the coefficients with the addition of random noise. This imputation process is replicated

other U.S. samples.³³ In my sample, only about half of the unadjusted income observations at the consumer-interview level reflect full income reporting.³⁴ The standard errors of my regression estimates are adjusted to reflect the multiply imputed nature of the income variable. The apparel expenditure and income variables are adjusted to real-2011 dollars using the all-items CPI for urban consumers. Table 6 presents a summary of the data.

For a preliminary exploratory analysis, I estimate non-parametric Engel curves for the total expenditure, purchase quantity, and average item price variables of three groups of apparel sub-categories which are likely to differ by visibility: “Outerwear” includes the Outerwear (‘Coats, jackets, and furs’) and Accessories sub-categories; “Middlewear” includes my ‘Shirts’ category (which includes both Sweaters (‘Sweaters and sweater sets’) and Shirts (‘Shirts, blouses and tops’) sub-categories), and the Bottoms (‘Pants, jeans, and shorts’) sub-category; finally, the “Underwear” category includes the Undergarments sub-category.³⁵ I rescale each variable by its median value, which is necessary for this visual comparison since the levels of each variable differ across categories. I aggregate the income variable into twenty bins and then perform a local polynomial regression of consumption variables on income.

Figures 3 –5 show the results of these regressions, where the predicted value by income bin is plotted at the average income for that bin. Figure 3 graphs average quarterly expenditure by category. It is roughly a counterpart to Figure 4 in Heffetz (2011), and my qualitative result

five times, and the five sets of income estimates together capture the variance in the imputed data. See “Multiple Imputation Manual” by the BLS for further details.

³³ Garner et al. (2009) report comparisons of income in the Consumer Expenditure Survey and the Current Population Survey (CPS) before and after income imputation: for 2002 and 2003, CEX income is about 75% of CPS income, but for 2004 to 2006, CEX imputed income is 94% of CPS income.

³⁴ In the portion of my sample from 2006 and later, 50.6% of consumer-interview level imputed income values are the same as their unadjusted counterparts. In 2004-2005 the BLS did not report the unadjusted income values.

³⁵ There are 17 sub-categories in total; the sub-categories not included here are: “Sport coats and tailored jackets,” “Suits,” “Vests,” “Dresses,” “Skirts,” “Hosiery,” “Nightwear and loungewear,” “Active sportswear,” “Uniforms,” “Costumes,” and “Footwear.”

Table 6: Data Description

Consumer units	Mean/ Proportion	(SD)
Age	43.1	(12.49)
Annual income	\$72,601	(67446)
Family size	2.72	(1.55)
Education < H.S.	0.12	
Education >= H.S., < College	0.57	
Education = College	0.20	
Education > College	0.11	
White, non-hispanic	0.68	
Black, non-hispanic	0.12	
Asian, non-hispanic	0.04	
Hispanic, any race	0.14	
Other race, non-hispanic	0.02	

Note: Demographic variables describe reference consumer.

Consumption variables	Shirts		Underwear	
	Mean	(SD)	Mean	(SD)
Number of items per quarter	1.76	(5.02)	0.74	(4.45)
Fraction with positive number	0.26	(0.437)	0.08	(0.276)
Average \$/item	\$22.80	(26.73)	\$11.16	(14.36)
Total expenditure per quarter	\$35.56	(145.35)	\$5.03	(28.772)
1st income quintile expenditure	\$17.82	(72.84)	\$3.28	(19.65)
2nd income quintile expenditure	\$22.38	(78.74)	\$4.06	(25.62)
3rd income quintile expenditure	\$29.61	(96.11)	\$4.63	(28.65)
4th income quintile expenditure	\$40.30	(118.92)	\$5.64	(29.45)
5th income quintile expenditure	\$67.71	(263.01)	\$7.54	(37.39)

that the slope of the income-expenditure curve is increasing according to visibility is consistent with his empirical findings using a broader and slightly older CEX data sample. The Engel curve for Underwear is flatter than that for Middlewear, and Middlewear is flatter than Outwear. Figures 4 and 5 compare average quarterly number of items and average item expenditure across categories, respectively. Note that the y-axis is the same for Figures 4 and 5, and we see some

Figure 3: Annual expenditure

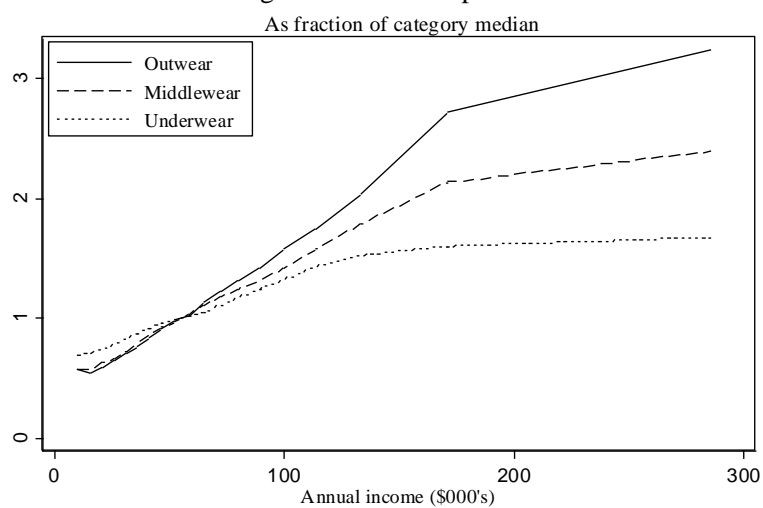


Figure 4: Number of items purchased quarterly

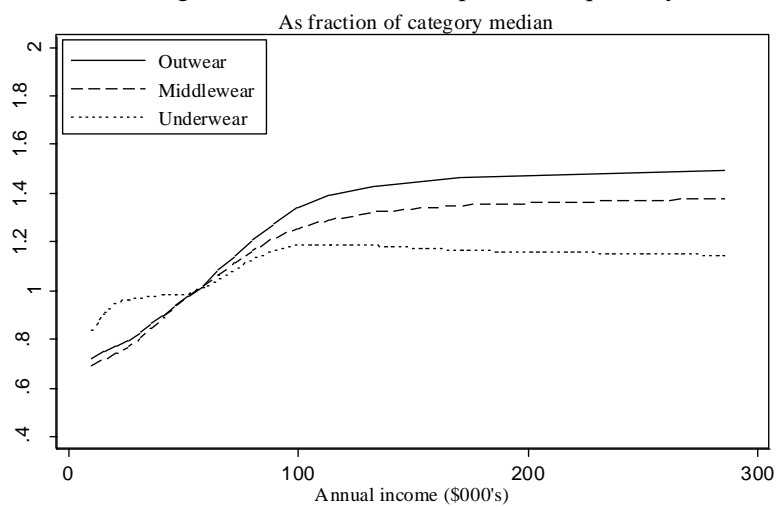
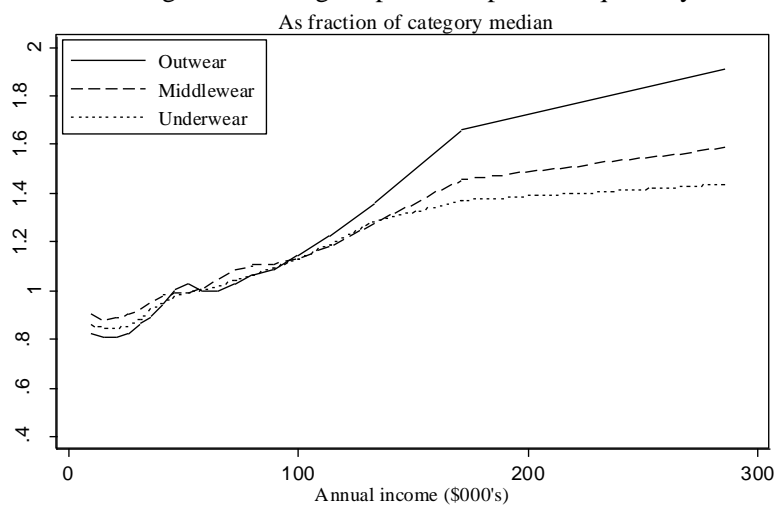


Figure 5: Average expenditure per item, quarterly



(statistically untested) evidence that the difference between Underwear and the visible categories is greater for number of items than for the average item expenditure.

To more rigorously estimate the effect of visibility on the Engel curves for quantity and quality, section 2.5 develops parametric regression models of quantity and quality choice which can control for demographic variables. Heffetz (2012) shows that demographic variables are important correlates for visibility expenditures, perhaps because different goods or services may be more or less visible for different demographic groups. If demographic variables that are correlated with income are also correlated with consumers' use of apparel as a status signal, omitting demographic variables could cause bias in the estimated effect of income on quantity and quality demand. The theoretical model in section 2.3 also shows how preference parameters influence the consumer's trade-offs between durable good attributes. Age, education level, and race of the reference consumer are all included as controls.³⁶ Family size is also included as a control; it is an important factor in predicting apparel quantity since apparel is consumed at roughly the individual level but the consumer units can include multiple individuals. Demographic variables for consumer units are available at the interview (quarterly) level, and I merge these variables from the consumer description files with the expenditure files at the consumer-quarter level.

My empirical application to test the effects of visibility compares only the Shirts and Underwear categories in an attempt to minimize functional differences. The change in visibility between Underwear and Outerwear might be greater, but functional differences are also likely to be greater. For example, an individual consumer uses roughly one item from her shirt and

³⁶ The results of Charles et al. (2009) indicate that a researcher could control for the effect of race on visible good spending by including reference income at the race-state cell. However, in my regression model the reduced-form relationships between race and visible good expenditure (which Charles et al. also document) are captured by controlling for race.

underwear stocks per day, and this may not hold for outerwear. Additionally, the Shirt category may be the most similar to Underwear in durability. Bils and Klenow (1998) use a structural model to estimate the durability of categories of goods in the Consumer Expenditure Survey, and their average estimated durability for the shirt and underwear categories are 2.5 and 2.0 expected life-years, respectively. The outerwear categories of goods have greater average estimated durability, 4.2 life-years.³⁷ A comparison of underwear and shirt consumption is similar in some ways to evaluating a quasi-experimental change from non-visibility to visibility.

2.5 Empirical Model

My central empirical research question is whether visibility has a greater effect on the elasticity of quantity with respect to income or the elasticity of quality with respect to income. The theoretical model shows how the level of “newness” or quality of a durable good could be distorted due to income signaling. However, the actual effect of visibility on durable good stock attributes depends on the functional form of utility, so the question of which attribute(s) actually have increasing income elasticity with respect to visibility is an empirical question.

Let V_A , V_Q , and V_W denote the effects of visibility on the elasticities of demand for newness, quality, and stock size with respect to income, respectively. In the theoretical model above, these effects are equal to the difference between the income elasticities of the implicit demand functions when the good is visible and their counterparts when the good is not visible. Let A^V (A^{NV}), Q^V (Q^{NV}), and W^V (W^{NV}) denote the demand for the attributes when the good is visible (not visible). Then the effects of visibility on the income elasticities can be expressed, respectively, as:

³⁷ The individual category estimates are: women’s blouses, 2.3; men’s shirts and nightwear, 2.7; women’s underwear, 1.8; men’s underwear, 2.2; women’s coats, 4.3; men’s suits and coats, 4.1.

$$\begin{aligned}
V_A &\equiv \varepsilon_{A^v y} - \varepsilon_{A^{nv} y}, \\
V_Q &\equiv \varepsilon_{Q^v y} - \varepsilon_{Q^{nv} y}, \\
\text{and } V_W &\equiv \varepsilon_{W^v y} - \varepsilon_{W^{nv} y}.
\end{aligned} \tag{11}$$

The effects of visibility on stock size and newness could be studied separately, but my empirical analysis studies the net effect of visibility on the income elasticity of per-period purchase quantity. In the CEX data, I observe N , the physical quantity of items purchased, and P , the average price per item, for each period of observation and category of apparel stock. As the budget constraint from the theoretical model indicates, $N = W/(2A - 1)$. Since N aggregates the consumer's choices of W and A , I would not be able to separately identify V_A and V_W . That is, if we observe that the income elasticity of N with respect to income is increasing with visibility, this could occur because average item age is decreased by visibility, stock size is increased by visibility, or both. I assume that price is a proxy for quality, so the effect of visibility on the elasticity of P with respect to income is a proxy for V_Q .

The elasticity of N with respect to income is exactly equal to the sum of the elasticity of stock size and the elasticity of average replacement age $R \equiv (2A - 1)$, since $N = W/R$. Expressing the elasticity of N in terms of W and average age A requires a slight adjustment³⁸:

$$\varepsilon_{Ny} = \varepsilon_{Wy} + \varepsilon_{Ay} \frac{2A}{2A-1}. \tag{12}$$

Let V_N denote the effect of visibility on the elasticity of N with respect to income. Equations (11) and (12) show that V_N is a slightly adjusted sum of the effects of visibility on W and A :

$$V_N = V_W + V_A \frac{2A}{2A-1}. \tag{13}$$

³⁸ This can be seen by: $R = 2A - 1 \rightarrow \frac{dR}{dy} = 2 \frac{dA}{dy} \rightarrow \frac{dR}{dy} \frac{y}{R} = \frac{dA}{dy} \frac{y}{A} \frac{2A}{2A-1} \rightarrow \varepsilon_{Ry} = \varepsilon_{Ay} \frac{2A}{2A-1}.$

If we could exogenously vary the good's visibility, we could determine whether visibility has a greater effect on the elasticity of quantity or quality with respect to income by calculating a “difference in differences” statistic $\overline{d_{NQ}^V}$, defined as the difference between the effect of visibility on quantity and the effect of visibility on quality:

$$\overline{d_{NQ}^V} \equiv V_N - V_Q = \left[\varepsilon_{N^V y} - \varepsilon_{N^{NV} y} \right] - \left[\varepsilon_{Q^V y} - \varepsilon_{Q^{NV} y} \right]. \quad (14)$$

I use the demands for durable good stock attributes from the theoretical model to develop regression models for estimating the elasticities of N and P with respect to income. The equations in (10) show that attribute demands depend on income, preference parameters, and prices, and they may also depend on status preference a and the lowest income if the good is visible. We could combine the demand functions for A and W to obtain a function for quantity demand per period, $N(y, a, \underline{y}, \beta, \mathbf{P})$ in terms of these variables. If we assume that this quantity function is separable in preference parameters, prices, and income such that the effect of income can be separated into the intrinsic effect that does not depend on visibility or a and the effect which arises if the good is visible, we could take the logarithm of that function and express quantity per period N for a given consumer i and category C at time t as:

$$\ln N_{itC} = \gamma_N \ln y_{it} + \varphi_N(a) \ln y_{it} + \theta_N(\beta_i) + \phi_N(\mathbf{P}_C). \quad (15)$$

Quality demand in the theoretical model depends on the same variables as A and W , so given another separability assumption an expression similar to (15) could be developed for Q_{itC} :

$$\ln Q_{itC} = \gamma_Q \ln y_{it} + \varphi_Q(a) \ln y_{it} + \theta_Q(\beta_i) + \phi_Q(\mathbf{P}_C). \quad (16)$$

The parameter γ_N (γ_Q) reflects the elasticity of quantity (quality) demand with respect to income that is attributable to intrinsic utility. The function $\varphi_N(a)$ ($\varphi_Q(a)$) reflects the distortion in the income elasticity of quantity (quality) demand that arises if the good becomes visible. The

theoretical model's assumption that preference for status is the same across consumers, as captured by a , is not likely to hold in real data about apparel consumption. Even if consumers care equally about status from all goods, they may not care equally about status from apparel consumption. However, as long as preference for status from apparel does not vary systematically with income, the $\varphi_N(a)$ ($\varphi_Q(a)$) term can capture the average effect of visibility across the distribution of status preferences. The functions $\theta_N(\beta_i)$ and $\phi_N(\mathbf{P}_C)$ ($\theta_Q(\beta_i)$ and $\phi_Q(\mathbf{P}_C)$) describe the influence of preference and price parameters on quantity (quality) demand, respectively. My regression models include controls for consumer characteristics to capture $\theta_N(\beta_i)$ ($\theta_Q(\beta_i)$), and category fixed effects will capture $\phi_N(\mathbf{P}_C)$ ($\phi_Q(\mathbf{P}_C)$).

Assuming a linear form for the functions $\theta_N(\beta_i)$ and $\theta_Q(\beta_i)$ in (15) and (16) above, the quantity and quality demands are:

$$\begin{aligned}\ln N_{itC} &= \gamma_N \ln y_{it} + \varphi_N(a) \ln y_{it} + \theta_N \beta_i + \phi_N(\mathbf{P}_C); \\ \ln Q_{itC} &= \gamma_Q \ln y_{it} + \varphi_Q(a) \ln y_{it} + \theta_Q \beta_i + \phi_Q(\mathbf{P}_C).\end{aligned}\tag{17}$$

I use an empirical specification to estimate the equations in (17), where the data are pooled across categories and interviews and separate income elasticities are estimated for each category:

$$\begin{aligned}\ln N_{itC} &= \sum_C \pi_{NC} \ln y_{it} + \lambda_N \mathbf{X}_i + \phi_N(\mathbf{P}_C) + \mu_{itCN}; \\ \ln P_{itC} &= \sum_C \pi_{QC} \ln y_{it} + \lambda_Q \mathbf{X}_i + \phi_Q(\mathbf{P}_C) + \mu_{itCP}.\end{aligned}\tag{18}$$

The variables in \mathbf{X}_i with marginal effects λ include age, education, race, and family size; these control variables are used to approximate the influence of the preference parameters. As mentioned above, category fixed effects will capture $\phi_N(\mathbf{P}_C)$ and $\phi_Q(\mathbf{P}_C)$. Note that the price parameter vector \mathbf{P}_C reflects the prices of quality and quantity relative to the numeraire good, which is different from P_{itC} , which reflects the consumer's choice of quality relative to quantity.

For a non-visible category, the income elasticity coefficients π_{NC} and π_{QC} reflect the influence of intrinsic utility alone (γ_N and γ_Q); for a visible category, if $a > 0$, the income elasticity coefficients also include the signaling effects $\phi_N(a)$ and $\phi_Q(a)$. If visibility is the only difference between two categories, the differences in their income elasticities capture the effects of visibility on the income elasticities, $\phi_N(a)$ and $\phi_Q(a)$. Income does not vary exogenously, although controlling for some observables such as age and education can decrease endogeneity that could cause bias in the elasticity estimate. It is important to stress that the estimated elasticities with respect to income will reflect correlation and not a causal relationship.

The actual equations used to estimate the elasticities are slightly modified versions of the equations in (18) due to the nature of the observed data. The observed quantity variable takes the form of counts. A Poisson regression model was estimated first, and a goodness-of-fit test of the Poisson model is rejected at any level of significance—i.e., the data are over dispersed and the Poisson assumption of equal variance and mean is rejected.³⁹ I estimate a negative binomial model instead, using the following regression equation:

$$N_{itC} = \exp \left(\sum_C \pi_{NC} \ln y_{it} + \lambda_N \mathbf{X}_{it} + \phi_N(\mathbf{P}_C) + \mu_{itCN} \right). \quad (19)$$

The error term μ_{itCN} reflects unobserved heterogeneity that is not captured by the regressors; if we assume that $\exp(\mu_{itCN})$ is gamma-distributed, then N follows a negative binomial distribution. I use the “NegBin2” version of the model, where the variance is assumed to be a quadratic function of the mean; in this case the dispersion parameter α is the coefficient on the quadratic term in the variance function (Cameron and Trivedi 1998). In addition to the control variables

³⁹ The zero-inflated probability (ZIP) model could also be considered. The ZIP model would be appropriate if some zero-quantity observations in the data reflected consumers who happened to not purchase in that quarter and other zero-quantity observations reflected consumers who would never purchase given any number of observed quarters. I assume that every consumer would have positive purchases given enough observations (i.e., that both apparel categories are necessities), so I do not use the ZIP model.

mentioned above, the \mathbf{X}_i vector here also contains indicator variables for the calendar month of the interview, since there is large seasonal variation in apparel purchase quantity.

To estimate the model of average item price, where price is a proxy for quality, I also use a modified version of the regression equation in (18). Since item expenditure is only observed for consumers with positive purchases, and the probability of purchase is positively correlated with income, I use a Heckman selection model to estimate item expenditure. If I ignored the selection bias, I would underestimate the elasticity of item price with respect to income. I use the dummy variables for calendar interview-month as the selection variable. The interview-month dummies are good predictors of the consumer's probability of positive quantity conditional on income, which is why they are included in the quantity regression (19). However, the dummies are weakly correlated with observed item prices (for example, the adjusted R-squared is 0.017 in a multivariate OLS regression of the interview-month dummies on average item price by category). Estimating the Heckman model involves two stages of estimation:

$$\begin{aligned} [i] \quad \Pr(N_{itC} > 0) &= \sum_C \pi_{QC}^{-1} \ln y_{it} + \phi_Q^{-1}(\mathbf{P}_C) + \boldsymbol{\lambda}_Q' \mathbf{M} + \eta_{itC}; \\ [ii] \quad \ln P_{itC} &= \sum_C \pi_{QC} \ln y_{it} + \phi_Q(\mathbf{P}_C) + \boldsymbol{\lambda}_Q' \mathbf{X}_i + \mu_{itCP}. \end{aligned} \quad (20)$$

The selection model is identified given the assumption that the interview-month dummies \mathbf{M} are correctly excluded from the second equation. The first equation (20)[i] estimates the probability of selection as a function of income, interview calendar month, and a category fixed effect that captures differences across consumers that are invariant within category. Conditional on selection, the second equation (20)[ii] is used to estimate quality choice. The error terms η_{itC} and μ_{itCP} are assumed to be jointly normally distributed.

If we assume that the fundamental difference between demand for a stock of shirts and demand for a stock of underwear is the visibility of shirts compared to the non-visibility of

underwear, and shirts and underwear are not substitutes, the difference between categories for an estimated elasticity with respect to income is a proxy for the effect of visibility on the elasticity. In this case, the empirical counterpart of the difference-in-differences statistic defined in (14) is a linear combination of coefficients from equations (19)⁴⁰ and (20)[ii]:

$$d_{NP}^V = (\pi_{N,Shirts} - \pi_{N,Underwear}) - (\pi_{P,Shirts} - \pi_{P,Underwear}). \quad (21)$$

Although I do not have enough observations per consumer to form a panel, the standard errors of my estimates are all clustered at the consumer level to capture unobserved individual effects that are correlated across variables, categories, or interviews for a given consumer and not captured by the λ_N and λ_Q terms. The standard errors of the estimates must also be adjusted for the multiply imputed income variable. As footnoted above, the BLS reports income estimates for five replications of the imputation process. Following the method of Dynan et al. (2004), I build the regression dataset by stacking each observation five times with a different estimate from the imputation process, and I correct my standard errors to reflect the presence of replicates by multiplying them by the square root of the number of replicates.

2.6 Results

Results of the quantity choice regression are shown in Table 7. The coefficients and dispersion parameter in this non-linear model are estimated using the log-likelihood method of maximum likelihood estimation and the Newton-Raphson technique. The quality choice results are found in Table 8; the selection equation results are shown below the main equation results, and the equations are estimated simultaneously using full maximum likelihood. Table 9 combines the estimated income elasticities from Tables 7 and 8 for ease of comparison.

⁴⁰ In the negative binomial regression model, the coefficient on a regressor which enters logarithmically is an elasticity (see Chapter 3 of Cameron and Trivedi (1998) for further details).

A first result seen in Table 9 is that only the quantity elasticity with respect to income is increased by visibility. A test of equality between $\pi_{N,Shirts}$ and $\pi_{N,Underwear}$ is rejected at the 1% level of significance. However, there is no statistical difference between the two categories' elasticity point estimates for quality.

Table 7: Quantity Regression Results

Dependent variable: Count of items		
Regression model: Negative binomial model		
Variable	Coefficient	(SE)
Log income x Shirts	0.153***	(0.022)
Log income x Underwear	0.049	(0.038)
Underwear	0.280	(0.404)
Age	-0.017	(0.013)
Age-squared	0.000	(0)
Family size	0.162***	(0.016)
Education >= H.S., < College	0.225**	(0.087)
Education = College	0.289**	(0.096)
Education > College	0.383***	(0.105)
Black, non-hispanic	-0.001	(0.084)
Asian, non-hispanic	-0.373***	(0.106)
Hispanic, any race	-0.107	(0.072)
Other race	0.239	(0.154)
Constant	-0.788**	(0.287)
N	1659210	
Log-likelihood	-1584044	
Pseudo-R2	0.014	
Dispersion parameter (α)	14.330	(0.034)

Notes: ***, **, * denote statistically different from zero at 1%; 5%; 10% level. SE's clustered by consumer. Regression also includes dummies for calendar interview month. Omitted categorical variables are Shirts, Education < H.S., White, non-hispanic.

Table 8: Quality Regression Results

Dependent variable: Log of average item price

Regression model: Heckman selection model (MLE method)

Variable	Coefficient	(SE)
Log income x Shirts	0.092***	(0.014)
Log income x Underwear	0.099***	(0.022)
Underwear	-0.492*	(0.232)
Age	-0.020***	(0.005)
Age-squared	0.000***	(0)
Family size	-0.082***	(0.007)
Education ≥ H.S., < College	0.119***	(0.035)
Education = College	0.283***	(0.039)
Education > College	0.326***	(0.043)
Black, non-hispanic	-0.092**	(0.031)
Asian, non-hispanic	0.096*	(0.047)
Hispanic, any race	0.053	(0.029)
Other race	-0.044	(0.061)
Constant	3.299***	(0.203)
Selection equation		
Log income x Shirts	0.096***	(0.009)
Log income x Underwear	0.057***	(0.011)
Underwear	-0.283*	(0.125)
Interview-month 2	-0.014	(0.025)
Interview-month 3	-0.055*	(0.026)
Interview-month 4	-0.183***	(0.026)
Interview-month 5	-0.198***	(0.028)
Interview-month 6	-0.179***	(0.028)
Interview-month 7	-0.181***	(0.025)
Interview-month 8	-0.192***	(0.028)
Interview-month 9	-0.143***	(0.028)
Interview-month 10	-0.153***	(0.025)
Interview-month 11	-0.164***	(0.028)
Interview-month 12	-0.152***	(0.028)
Constant	-1.601***	(0.095)
N (Uncensored observations)	1659210 (269855)	
Log-likelihood	-1002173	

Notes: ***, **, * denote statistically different from zero at 1%; 5%; 10% level. SEs clustered by consumer. Omitted categorical variables in main equation: Shirts, Education < H.S., White, non-hispanic; omitted in selection equation: Shirts, Interview-month 1.

Table 9: Summary of Elasticity Estimates

Category	Elasticity of Number of Items with respect to Income	95% CI Lower bound	95% CI Upper bound	Elasticity of Avg Item Price with respect to Income	95% CI Lower bound	95% CI Upper bound
Shirts	0.153	0.111	0.196	0.092	0.066	0.119
Underwear	0.049	-0.025	0.123	0.099	0.056	0.143

Notes: See Tables 3 and 4 for full results of regression models. Standard errors are clustered by consumer.

In the within-category comparisons, I find that the elasticity of quantity with respect to income is larger than the elasticity of quality with respect to income for Shirts only. $\pi_{N,Shirts}$ is greater than $\pi_{Q,Shirts}$ at the 5% level of significance. The difference in elasticities between variables is not significant for the Underwear category. Note that comparing the number of items elasticity with the item price elasticity, within each visibility category, is an “apples to apples” comparison in a sense since either elasticity reflects the total expenditure elasticity when the other variable is held constant.⁴¹

A test of the hypothesis that the effect of visibility on the quantity elasticity is the same as its effect on the quality elasticity can be rejected at the 5% level of significance (the p-value from the Wald test is 0.02). Despite the size of the standard errors on the elasticity estimates due to my adjustment for the multiply imputed income variable, this result provides some support for a hypothesis that the difference-in-differences statistic is positive:

⁴¹ This fact arises since the total expenditure elasticity with respect to income is mathematically equal to the sum of the average price elasticity with respect to income and the average number of items elasticity with respect to income: $e = n * p \rightarrow \frac{de}{dy} = p \frac{dn}{dy} + n \frac{dp}{dy} \rightarrow \frac{de}{dy} \frac{y}{e} = \frac{dn}{dy} \frac{y}{n} + \frac{dp}{dy} \frac{y}{p}$. Hence, the elasticity of number of items with respect to income is the same as the total expenditure elasticity with price held constant: $\frac{dn}{dy} \frac{y}{n} = \frac{de}{dy} \frac{y}{e} \Big|_{\bar{p}}$, and the elasticity of item price with respect to income is the same as the total expenditure elasticity with number of items held constant: $\frac{dp}{dy} \frac{y}{p} = \frac{de}{dy} \frac{y}{e} \Big|_{\bar{n}}$.

$$d_{NP}^V = (\pi_{N,Shirts} - \pi_{N,Underwear}) - (\pi_{P,Shirts} - \pi_{P,Underwear}). \quad (22)$$

These results are robust to alternate modeling assumptions, including alternate measures of consumer income and controls for time-varying unobservables. During the time period of my data, the U.S. experienced a recession, and the nominal cost of apparel actually fell, so it is important to test whether time-varying factors are driving my findings. Between January 2001 and January 2011, the overall CPI rose by about 25% while the apparel CPI *decreased* by about 6%, so I first deflate apparel expenditure by the apparel CPI instead of the overall CPI to make sure that my estimated average item price elasticities do not spuriously reflect correlated changes in income and apparel prices over time. Using the alternate CPI, the income elasticity of average item price is 9.38 for Shirts and 9.95 for Underwear, and the elasticities are still not statistically different from one another. Including a time trend in the baseline regressions has a similarly negligible effect on the number of items and average item price elasticity estimates. Table 10 shows a summary of the elasticity estimates with fixed effects for date of interview (measured in months) added to the baseline regression models. The quantity elasticities are virtually unchanged; the quality elasticities are both greater in magnitude, but we still cannot reject equality of the quality elasticities across categories.

Table 10: Summary of Elasticity Estimates with Interview Date Fixed Effects

Category	Elasticity of	95%	95%	Elasticity of	95%	95%
	Number of Items	CI	CI	Avg Item Price	CI	CI
	with respect to	Lower	Upper	with respect to	Lower	Upper
	Income	bound	bound	Income	bound	bound
Shirts	0.153	0.112	0.194	0.159	0.135	0.184
Underwear	0.049	-0.023	0.121	0.139	0.097	0.182

Notes: Full results of regression models available from author by request. Standard errors are clustered by consumer.

When alternate variables are used in place of imputed income, the magnitudes of the elasticity estimates are changed, but my qualitative findings still hold. Table 11 summarizes the estimated elasticities with respect to reported income, including only consumers with complete income reporting (i.e., for whom imputed income matches reported income). Table 12 summarizes the estimated elasticities with respect to total expenditure, where total expenditure is a proxy for income as in Charles et al. (2009) or Bils and Klenow (2001).

Table 11: Summary of Elasticity Estimates for Full Income Reporters

Category	Elasticity of Number of Items with respect to Income	95% CI Lower bound	95% CI Upper bound	Elasticity of Avg Item Price with respect to Income	95% CI Lower bound	95% CI Upper bound
Shirts	0.138	0.119	0.157	0.048	0.035	0.061
Underwear	0.049	0.014	0.083	0.059	0.037	0.080

Notes: Full results of regression models available from author by request. Standard errors are clustered by consumer.

Table 12: Summary of Elasticity Estimates Using Expenditure as Proxy for Income

Category	Elasticity of Number of Items w.r.t. Total Expenditure	95% CI Lower bound	95% CI Upper bound	Elasticity of Avg Item Price w.r.t. Total Expenditure	95% CI Lower bound	95% CI Upper bound
Shirts	0.578	0.548	0.607	0.183	0.164	0.202
Underwear	0.466	0.419	0.514	0.178	0.150	0.207

Notes: Full results of regression models available from author by request. Standard errors are clustered by consumer.

The average price elasticities are significantly smaller when the dataset is restricted to full income reporters, although they are still not statistically different between categories. It is important to note that higher-income consumers are less likely to be full income reporters; the average value of imputed income for incomplete reporters in the regression dataset is 25% greater than the average income for full income reporters. The results in Table 11 and this fact

together suggest that the average item elasticities may actually be increasing in income rather than constant. When total expenditure is used as a proxy for income, all the elasticity estimates are larger (since total expenditure is, on average, less than income), but the central results from Table 9 still hold: the quantity elasticity is statistically larger for Shirts than for Underwear, and the quality elasticity is not statistically different between categories.

2.7 Discussion

My empirical results suggest some implications for a theoretical model of status-seeking with visible apparel consumption. The income elasticity of demand for quantity is not statistically different from zero for the Underwear category, which suggests that the intrinsic value of apparel quantity is not strongly correlated with income. The point estimate of the income elasticity of demand for Underwear quality, which is statistically different from zero at the 1% level of significance⁴², is twice as large as the quantity estimate, but this difference is not statistically significant. In the Shirts category, I do find that the income elasticity of quantity is statistically larger than the income elasticity of quality.

In my comparisons of elasticity estimates between categories for a given variable, I find evidence that visibility increases the elasticity of quantity with respect to income but does not increase the elasticity of quality with respect to income. This suggests the possibility that a signaling equilibrium could exist where quantity attribute(s) of the apparel stock are used as

⁴² This result should not be construed as inconsistent with the theoretical model. Although the theoretical model predicts that the income elasticity of quality is zero when the durable good is not visible, this result obtains from the functional form assumption for utility, which was chosen for its tractability. Alternate utility functions could yield positive income elasticities for any or all attributes of a non-visible durable good; as long as the income elasticities for Underwear quality and quantity are not non-negative, they are not inconsistent with the broader theory of the signaling model.

status signals. A hypothesis that the effect of visibility on the income elasticity of quantity is the same as its effect on the income elasticity of quality is rejected at the 5% level of significance.

Another potential explanation for my results is that the newness or stock size of a consumer's apparel wardrobe may be more visible than its quality. My theoretical model has assumed that all attributes are equally visible, but if visibility did differ across attributes the equilibrium status signal could depend on the attributes' visibility. For apparel goods, newness may be very visible, given the focus of the apparel industry on novelty. If status is allocated through repeated social interaction, stock size is also likely to be somewhat visible. Quality, as proxied by price, seems likely to be at least partially visible. Additionally, if name-brand items have higher prices which can easily be observed, paying a higher price per item could be an effective signal of expenditure. However, if preferences satisfy the single-crossing property, Bagwell and Bernheim (1996) show that Veblen effects do not exist—i.e., high-income consumers would not choose a higher-priced brand for the same quality level. Under the single-crossing assumption, high-income consumers would only signal using quality if the utility-vs.-price tradeoff was better for quality than for quantity.

A necessary caveat is that my empirical results reflect the consumption behaviors of a sample of U.S. working-age consumers during 2004-2010. Any status signaling mechanisms that exist in this sample might not be the same as those that exist for other goods, other populations, or other time periods. A longer window of data could be used to examine if consumers' quantity or quality status signaling is constant over time, in an approach similar to Bils and Klenow (2001). Further research could also investigate the difference between quantity and quality distortions due to visibility for durable versus non-durable goods. If newness cannot be used as a status signal for consumable goods, the quantity distortion may be smaller than it is

for durable goods. Future research could also investigate the environmental impact of status signaling through quantity rather than quality, which could be significant for apparel given its large environmental impacts (Claudio, 2007).

CHAPTER 3

THE PORTER HYPOTHESIS IN A MODEL OF LIMITED ATTENTION TO WASTE PRODUCTION

3.1. Introduction

Traditionally, environmental policy analysis has taken a cost-benefit approach which assumes that environmental regulation must increase producers' internal costs, at least weakly, but regulation can still increase net social benefits by reducing external costs. An optimal regulatory framework efficiently trades off private costs and public benefits, with no possibility of *private benefits* increasing for regulated producers. In contrast, a wide range of studies in the Business and Economics literatures have shown how environmental regulation could actually benefit firms, or at least not make them worse off (Porter 1991, Ambec and Barla 2002, Mohr 2002, Jaffe et al. 1995, King and Lenox 2001, King and Lenox 2002, Porter and van der Linde 1995). This literature builds on Porter's original hypothesis that environmental regulation could benefit firms via increased innovation or other mechanisms (Porter 1991). Not surprisingly, Porter's hypothesis is strongly disputed by proponents of traditional environmental economics (Palmer et al. 1995). A central question in the dispute is whether or not firms are always perfectly profit-maximizing.

In this essay, I develop a model of a production process where the firm's production manager exhibits a form of behavioral bias known as "limited attention." I show that a disposal fee which satisfies Porter's hypothesis can theoretically exist in this model—the firm can increase its *private benefit* as it chooses a more efficient combination of inputs, while net social benefits also increase since the external cost of waste disposal is now borne by the firm. This result arises from three central assumptions in the model: (1) the efficiency of input use in the production process varies across inputs (i.e., some inputs are "wasted" more than others); (2) the

manager pays “limited attention” to the relative efficiency of the inputs (which results in the firm not perfectly minimizing costs); (3) environmental regulation in the form of a disposal fee makes the waste stream salient, so the manager learns the inputs’ relative efficiencies.

However, further analysis of the model reveals the limited potential for real-world environmental policy to improve firms’ internal cost-minimization through this mechanism. First, similarly to Mohr (2002), I show that a disposal policy which satisfies Porter’s hypothesis is not necessarily the optimal policy. Second, I show that if the social disposal cost of waste is not homogeneous across wasted inputs, a flat disposal fee combined with limited attention bias can actually cause the policy to back-fire and increase the social cost of the waste stream.

The rest of the essay proceeds as follows. Section 3.2 presents an overview of the related literature and motivation for this paper, and section 3.3 introduces the theoretical model. Section 3.4 analyzes the potential for Porter’s hypothesis to hold in the model, and section 3.5 describes the result satisfying Porter’s hypothesis in a numerical version of the model. Section 3.6 presents some additional model analyses. Section 3.7 concludes.

3.2 Literature and Motivation

Porter hypothesizes that if environmental regulation increases innovation, it could actually benefit the regulated industry in the long run; he cites Germany and Japan’s export success and environmental stringency as evidence that “environmental protection does not hamper competitiveness” (Porter 1991). Porter and van der Linde (1995) further develop the concept of “win-win” environmental regulation—i.e., regulation which benefits the environment as well as regulated firms; they argue that regulations can be beneficial since firms do not always make perfectly optimal choices due to “incomplete information, organizational inertia, and

control problems.” Imperfect use of information has also been cited in later literature as a reason why firms may not perfectly maximize profits (King and Lenox 2001, King and Lenox 2002).

None of these papers formally model “limited attention” to explain why firms might over-pollute from an internal standpoint, but together they assert that a firm’s desire to prevent waste for environmental reasons (whether government-mandated or internally motivated) can lead to the firm actually decreasing its costs. The empirical literature which tests Porter’s hypothesis has offered mixed results. Jaffe et al. (1995) study over 100 papers which analyze the effect of environmental regulation on U.S. competitiveness in manufacturing, and they find little evidence of a negative relationship between the two. King and Lenox (2002) do find some empirical evidence that firms under-invest in waste prevention. Damon and Khanna (1999) study the effect of the EPA’s 33/50 voluntary toxic release prevention program on firm economic performance, and they propose that firms could benefit from the program by “using their chemical inputs more efficiently (and increasing the productivity of chemical inputs).” On the other hand, when Rassier and Earnhart (2010) test the effect of clean water regulation on chemical manufacturing firms, they find that regulation increases firms’ costs, so their test of Porter’s hypothesis is rejected. See Ambec et al. (2013) for additional examples.

In a traditional framework where profit-maximizing firms are assumed to perfectly minimize internal costs, there is little (if any) possibility for “win-win” environmental regulation. In a counterpoint to Porter and van der Linde (1995), Palmer et al. (1995) show how Porter’s hypothesis is not plausible in a standard economics framework; since regulations are an additional constraint on firm actions, the regulated outcome simply cannot be better than the unregulated outcome. I discuss a parallel result in section 4.3.1 below: if the firm manager is

perfectly rational and does not exhibit limited attention bias, there is no potential for Porter's hypothesis to hold in my model.

However, various researchers have shown how Porter's hypothesis could theoretically hold under a traditional profit-maximization assumption if market failures or other externalities interact with the environmental externality. For example, Ambec and Barla (2002) show the benefit of regulation to a firm facing a principal-agent problem, and Mohr (2002) shows how regulations can benefit firms in an industry with external benefits to innovation. Despite the potential for Porter's hypothesis to hold in Mohr's model, he shows how the policy which satisfies the hypothesis may not actually be the optimal policy.

This essay makes use of the concept of limited attention from the behavioral economics literature to identify a new setting which can potentially support Porter's hypothesis. The model developed here relies on the same reasoning as Ambec and Barla (2002) and Mohr (2002)—Porter's hypothesis can hold if market imperfections interact with the environmental externality— but in this new setting the “market failure” exists within the firm itself. Limited attention on the part of firm managers is one of many potential behavioral biases through which the imperfect profit-maximization posited by Porter and van der Linde (1995) and King and Lenox (2001, 2002) could result.

Limited attention is a heuristic form of decision-making which reflects the psychology literature's experimental finding that humans have finite attention resources (DellaVigna 2009). In the model of DellaVigna (2009), the degree of inattention associated with a given piece of information is decreasing in the salience of the information and increasing in the number of competing stimuli. In the model analysis below, I consider only two potential degrees of inattention: none (this is called the “full attention” case and in it the manager is fully rational and

fully informed), or some (this is called the “limited attention” case and in it the manager is assumed to simplify information about production waste using an average-weighting heuristic).

The previous literature on limited attention has almost exclusively studied consumer behavior (e.g., Chetty, Looney, and Kroft 2009, Pope 2009; see DellaVigna 2009 for earlier examples). One exception is Lacetera, Pope, and Sydnor (2012), who consider limited attention to used-car odometer readings on the part of both wholesale firms and final consumers; they find evidence for limited attention by consumers but not by firms. Perhaps this is not surprising, since it does not seem particularly plausible that a meaningful number of firms are “leaving \$10 bills on the ground” due to any type of behavioral bias (Palmer et al. 1995). However, proponents of Porter’s hypothesis assert that one source of “win-win” environmental regulation is the ability of firms to both cut costs and reduce pollution waste. In the remainder of this essay I show how a firm manager’s limited attention to waste production could indeed make it possible for environmental policy to satisfy Porter’s hypothesis.

3.3 Model

Assume that the firm produces a single output Q from inputs $r_1 \dots r_n$ according to a production technology $f(\cdot)$ which is not perfectly efficient; for each unit of an input r_i , a fraction $(1 - \alpha_i)$, where $0 < \alpha_i < 1$, is wasted during the production process. Hence, the production function is given by:

$$Q = f(\alpha_1 r_1, \alpha_2 r_2, \alpha_3 r_3, \dots, \alpha_n r_n).$$

The firm disposes of the wasted fractions of each input. I assume that the firm manager can costlessly observe input use and the total volume of waste product, denoted by w , which is equal to the sum (in volume equivalence) of the waste from each input:

$$w = \sum_{i=1}^n (1 - \alpha_i) r_i.$$

3.3.1 Full Attention

If the firm manager has perfect information about each input's waste parameter α_i and price p_i , she determines the optimal input pairs (r_i^F, r_j^F) for every (i, j) by solving the cost-minimization problem:

$$\begin{aligned} \min \sum_{i=1}^n p_i r_i, \\ \text{subject to } Q = f(\alpha_1 r_1, \alpha_2 r_2, \alpha_3 r_3, \dots, \alpha_n r_n). \end{aligned}$$

Let f_i denote the derivative of $f(\cdot)$ with respect to input r_i . At an interior solution, the ratio of marginal products must equal the ratio of marginal costs for every input pair (i, j) , such that (r_i^F, r_j^F) satisfy:

$$(r_i^F, r_j^F): \frac{\alpha_i f_i}{\alpha_j f_j} = \frac{p_i}{p_j}.$$

Note that the volume of waste produced does not directly affect the manager's input decisions if disposal is costless.

3.3.2 Limited Attention

Now suppose that the firm manager is inattentive to the relative contribution of each input to its waste stream and only considers the total waste volume w . Given the observed waste volume w , the manager makes the simplifying assumption that the waste proportion α_i for each input i is equal to $1 - \bar{\alpha}$, where $\bar{\alpha}$ denotes the average proportion of input volume across input materials:

$$1 - \bar{\alpha} = \frac{w}{\sum_{i=1}^n r_i}.$$

Given this form of limited attention bias, the manager will choose input pairs (r_i^L, r_j^L) for every (i, j) which satisfy a different cost-minimization problem:

$$\begin{aligned} \min \sum_{i=1}^n p_i r_i, \\ \text{subject to } Q = f(\bar{\alpha}r_1, \bar{\alpha}r_2, \bar{\alpha}r_3, \dots, \bar{\alpha}r_n). \end{aligned}$$

The optimality condition given limited attention does not make use of the true α_i parameters; it is given by:

$$(r_i^L, r_j^L): \frac{f_i}{f_j} = \frac{p_i}{p_j}.$$

Comparing the conditions for (r_i^F, r_j^F) with full attention to those for (r_i^L, r_j^L) with limited attention, it is clear that limited attention causes r_i to be under (over)-used if α_i is greater (less) than $\bar{\alpha}$. In other words, limited attention causes the firm manager to deviate from the efficient input allocation by overestimating the marginal product of inputs that are wasted at a higher-than-average rate and underestimating the marginal product of inputs that are wasted at a lower-than-average rate. Both effects cause the firm's average waste level to be higher than optimal.

3.4 Policy Analysis

In this section, I show how implementing environmental policy in the form of a disposal fee could make the firm better off if (a) the firm manager experiences limited attention bias of the form modeled above and (b) the regulation makes the content of the waste stream salient to the firm manager, so that she now acts with perfect information about the waste parameters

instead of assuming that all inputs have the same proportional contribution to waste.⁴³ Assume that the firm now faces a volumetric disposal cost $t > 0$ per unit of w .

3.4.1 Regulation with Full Attention

If the manager does not suffer from limited attention bias, regulation weakly decreases firm profits. The manager now solves the cost minimization problem:

$$\begin{aligned} \min \sum_{i=1}^n p_i r_i + t \sum_{i=1}^n (1 - \alpha_i) r_i, \\ \text{subject to } Q = f(\alpha_1 r_1, \alpha_2 r_2, \alpha_3 r_3, \dots, \alpha_n r_n). \end{aligned}$$

The optimality condition (r_i^t, r_j^t) for an interior solution with disposal regulation is that the ratio of effective marginal products must equal the ratio of disposal-inclusive marginal costs for every input pair (i, j) :

$$(r_i^t, r_j^t): \frac{\alpha_i f_i}{\alpha_j f_j} = \frac{p_i + t(1 - \alpha_i)}{p_j + t(1 - \alpha_j)}.$$

Let $\tilde{d}(w)$ denote the marginal social cost of disposal of waste volume w . If the marginal social cost of disposal is constant with respect to waste volume, equal across inputs, and equal to d , then setting $t = d$ makes the manager's solution with full attention also equal to the socially optimal production method. However, as long as $t > 0$, the cost of producing output Q strictly increases and profits weakly decrease; profits strictly decrease unless the firm faces perfectly inelastic demand.

⁴³ I assume that the manager's new knowledge of the waste stream components does not cause her to begin acting with limited attention towards another part of the production process. The manager's cost of awareness could be thought of as an additional fixed disposal fee, which would not affect her optimal input ratios.

3.4.2 Regulation with Limited Attention

If the manager exhibits limited attention bias as described in section 3.3.2 above and the implementation of a disposal fee causes the manager to become attentive to the true waste parameters $\alpha_i \dots \alpha_n$ due to the waste stream's salience, then the disposal fee regulation has the possibility of making the firm better off. The manager's cost-minimization problem is the same here as it is in the case of full attention with disposal regulation, so the input pairs (r_i^t, r_j^t) satisfy:

$$(r_i^t, r_j^t): \frac{\alpha_i f_i}{\alpha_j f_j} = \frac{p_i + t(1 - \alpha_i)}{p_j + t(1 - \alpha_j)}.$$

The firm is made better off by regulation if the inefficiency losses due to limited attention outweigh the disposal costs at optimal input levels. In section 3.5, I study a production function with two inputs and describe the conditions which must be met for Porter's hypothesis to hold and the firm whose manager exhibits limited attention bias to be made better off by regulation.

3.5 Numerical Model

Suppose the firm faces a Cobb-Douglas production function with two inputs whose waste parameters are α_1 and α_2 , respectively, such that:

$$Q = (\alpha_1 r_1)^A (\alpha_2 r_2)^B.$$

Suppose, without loss of generalization, that input 1 is less wasteful—i.e., $\alpha_1 > \alpha_2$. The relevant derivatives are $f_1 = A r_1^{-1} Q$ and $f_2 = B r_2^{-1} Q$.

If the manager pays full attention to the waste parameters, her input choices satisfy the cost minimization constraint:

$$\frac{A \alpha_1 r_2}{B \alpha_2 r_1} = \frac{p_1}{p_2},$$

and the production feasibility constraint:

$$r_2 = Q^{\frac{1}{B}}(\alpha_1 r_1)^{-\frac{A}{B}}(\alpha_2)^{-1}.$$

These two equations can be solved for the optimal input pair without regulation:

$$r_1^F = \left(\frac{Q}{\alpha_1^A \alpha_2^B} \right)^{\frac{1}{B+A}} \left(\frac{A p_2 \alpha_1}{B p_1 \alpha_2} \right)^{\frac{B}{B+A}},$$

$$\text{and } r_2^F = \left(\frac{Q}{\alpha_1^A \alpha_2^B} \right)^{\frac{1}{B+A}} \left(\frac{B p_1 \alpha_2}{A p_2 \alpha_1} \right)^{\frac{A}{B+A}}.$$

If the manager exhibits limited attention bias, the input choices must still satisfy the production constraint, but the cost minimization condition will ignore the individual waste parameters:

$$\frac{A r_2}{B r_1} = \frac{p_1}{p_2}.$$

Hence, the unregulated firm with limited attention will choose a different input pair:

$$r_1^L = \left(\frac{Q}{\alpha_1^A \alpha_2^B} \right)^{\frac{1}{A+B}} \left(\frac{A p_2}{B p_1} \right)^{\frac{B}{B+A}},$$

$$\text{and } r_2^L = \left(\frac{Q}{\alpha_1^A \alpha_2^B} \right)^{\frac{1}{A+B}} \left(\frac{B p_1}{A p_2} \right)^{\frac{A}{B+A}}.$$

A comparison of r_1^L to r_1^F and r_2^L to r_2^F shows that limited attention causes the manager to under (over)-use the relatively more (less)-efficient input 1 (2).

Finally, consider the firm manager's input choices when it faces a volumetric disposal cost, t , and experiences full attention. The optimality condition is now

$$\frac{A \alpha_1 r_2}{B \alpha_2 r_1} = \frac{p_1 + t(1 - \alpha_1)}{p_2 + t(1 - \alpha_2)},$$

and the input choices are given by:

$$r_1^t = \left(\frac{Q}{\alpha_1^A \alpha_2^B} \right)^{\frac{1}{A+B}} \left(\frac{A(p_2 + t(1 - \alpha_2))}{B(p_1 + t(1 - \alpha_1))} \right)^{\frac{B}{B+A}} \left(\frac{\alpha_1}{\alpha_2} \right)^B,$$

$$\text{and } r_2^t = \left(\frac{Q}{\alpha_1^A \alpha_2^B} \right)^{\frac{1}{A+B}} \left(\frac{B(p_1 + t(1 - \alpha_1))}{A(p_2 + t(1 - \alpha_2))} \right)^{\frac{A}{B+A}} \left(\frac{\alpha_2}{\alpha_1} \right)^A.$$

Comparing r_1^L to r_1^t and r_2^L to r_2^t shows that regulation causes the manager with limited attention to increase the use of input 1 and decrease the use of input 2.

Under what conditions could Porter's hypothesis hold in this case? Regulation makes the firm whose manager exhibits limited attention bias better off if the cost of the input bundle (r_i^L, r_j^L) is greater than the cost of bundle (r_i^t, r_j^t) plus the disposal cost, or equivalently if:

$$p_1(r_1^t - r_1^L) + p_2(r_2^t - r_2^L) + t((1 - \alpha_2)r_2^t + (1 - \alpha_1)r_1^t) < 0.$$

The third term above must be positive since $t > 0$. Since input 1 is less wasteful than input 2, limited attention causes input 1 to be under-utilized—i.e., $r_1^L < r_1^t$ and the first term above is positive. However, $r_2^L > r_2^t$ and the second term is negative; this drives the result that Porter's hypothesis could be satisfied. Regulation makes the firm better off only to the extent that input 2 is significantly over-utilized in the case of limited attention. This condition becomes less likely to hold as the spread between the α_i 's decreases. Note that regulation is also less likely to make the firm better off as the disposal fee t increases, since from the manager's perspective the benefit of t is binary: it causes the manager to learn the α_i 's if it is greater than zero but offers no marginal benefit for increases above zero.

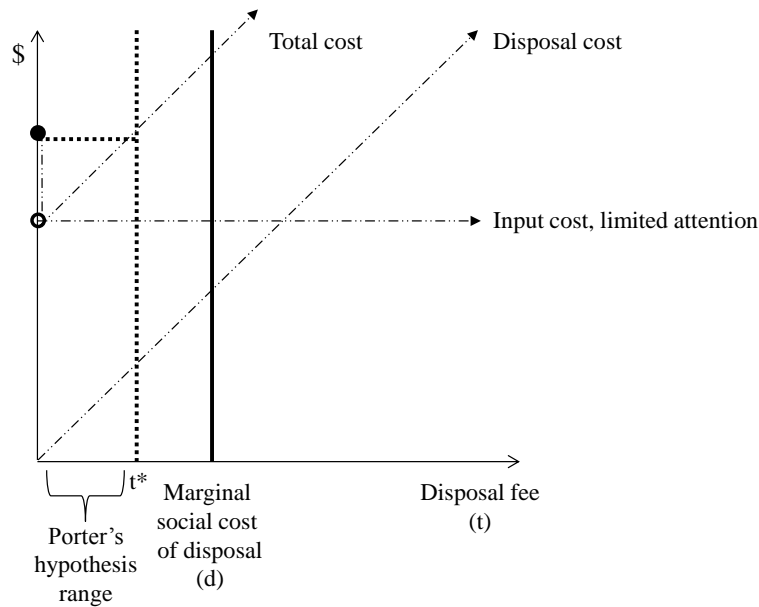
3.6 Model Applications

3.6.1 Optimal Disposal Fee

Although Porter's hypothesis may hold in the model above, it is not necessarily the case that a policy which satisfies Porter's hypothesis will be an optimal policy from a social planner's perspective. In fact, in this model, the optimal policy is independent of whether Porter's hypothesis holds or not. Figure 6 illustrates the costs faced by the manager with limited attention and shows that the range of disposal fees t for which Porter's hypothesis holds (which is given

by $(0, t^*)$) is independent of the true marginal social cost of disposal, d , which may be within the Porter's hypothesis range or above it. Note that for this analysis, we must focus on the case where the firm manager exhibits limited attention bias, since this is the only way for Porter's hypothesis to be satisfied in the model.

Figure 6: Cost of Production with Limited Attention



Mohr (2002) also finds the result that the optimal policy may not satisfy Porter's hypothesis, in his setting where externalities to innovation give rise to the potential for Porter's hypothesis to hold. He shows that it may be preferable in this setting to choose a policy which causes the environmental externality to increase by a relatively small amount while increasing output by relatively large amount, rather than limiting policy selection to options which strictly decrease the environmental externality. In a sense, environmental regulation causes the production possibilities frontier of the economy to expand as it spurs externalities in innovation.

3.6.2 Policy Back-Fire

Suppose now that the model is extended to allow for inputs with different social costs of disposal (though still assuming the marginal costs are constant with respect to volume), and let the social cost of disposal be equal to d_i for input i . The differences in social costs of disposal across inputs can be thought of as differing levels of toxicity, or differences in difficulty of physical waste handling, or differences in the time it takes hazardous materials to become inert. If product-specific disposal fees are feasible, and the fee t_i for each input i is set equal to the social cost of disposal d_i , then the firm manager who exhibits full attention also attains the socially optimal input trade-off:

$$\left(r_i^{t_i}, r_j^{t_j}\right) : \frac{\alpha_i f_i}{\alpha_j f_j} = \frac{p_i + t_i(1 - \alpha_i)}{p_j + t_j(1 - \alpha_j)} = \frac{p_i + d_i(1 - \alpha_i)}{p_j + d_j(1 - \alpha_j)}.$$

However, if product-specific disposal fees are not feasible (i.e., the policymaker is constrained to $t_i = t_j = t$) and the firm manager exhibits limited attention bias, in this extended model there is the potential for a disposal fee to “back-fire” and actually lead the firm manager to rationally increase the total social disposal cost of its waste stream. This result arises if inputs with relatively smaller social costs of disposal are relatively more wasted in the production process. Intuitively, if inputs with relatively smaller social costs of disposal are relatively more inefficient in the production process, and a homogeneous disposal fee is implemented, when the firm manager pays full attention to the inputs’ waste parameters she will shift the input allocation away from the inputs with smaller social costs of disposal and towards the inputs with higher social costs of disposal.

The result is easy to see for the two-input case analyzed above. The potential for policy back-fire arises with the scenario $\alpha_1 > \alpha_2$ and $d_1 > d_2$ —that is, if input 1 is more efficient in production yet also more costly to dispose. The effect of regulation on total waste is equal to:

$$w^t - w^L = [(1 - \alpha_1)d_1(r_1^t - r_1^L)] + [(1 - \alpha_2)d_2(r_2^t - r_2^L)].$$

The first bracketed term on the right-hand side of the equation above is greater than zero, and the second term is negative (our assumption that $\alpha_1 > \alpha_2$ means that $r_1^t > r_1^L$ and $r_2^L > r_2^t$, as described in section 3.5 above); the disposal policy “back-fires” if the second term has a greater absolute value. Hence, the effect of regulation on total waste can be positive if d_2 is sufficiently smaller than d_1 and α_2 is sufficiently smaller than α_1 .

3.7 Conclusion

This essay has presented a simple model of a waste-generating production process and a firm manager who may not make full use of information about production inefficiencies due to the behavioral bias of limited attention. Specifically, I assume that the manager with limited attention makes a simplifying assumption using a decision heuristic, and she assumes that all inputs are proportionally equal components of the waste stream rather than some inputs being wasted more than others. This scenario gives rise to the potential for “win-win” environmental regulation of waste disposal. If the implementation of a disposal fee causes the firm manager to become attentive to the true waste-generating process, and if the disposal fee is not too high and the true contribution of inputs to waste is sufficiently heterogeneous, then Porter’s hypothesis can hold and the disposal fee can improve both firm profits and net social benefits.

However, one cannot conclude from the results of this essay that trying to satisfy Porter’s hypothesis is a feasible goal for government regulation. As Mohr (2002) points out, a heavy informational burden is required in order to choose regulation with this goal. The informational burden is arguably even heavier in this essay’s model than in Mohr’s, which studies market

externalities.⁴⁴ Consider this: in any attempt to improve firms' production processes through environmental regulation, policy-makers would essentially be doing the job of the firm managers themselves and trying to assess whether the firm was perfectly profit-maximizing. Since it is not feasible for the government to obtain this necessary information to show that the disposal fee would make the firm better off, and considering the potential for "policy back-fire" as discussed in section 3.6.2, it seems that this essay offers theoretical, rather than prescriptive, results about the potential for regulation to satisfy Porter's hypothesis.

Finally, a potential concern for the generalizability of the model in this essay could be that the situation it presents may be less likely to persist in the long run than to exist in the short run. Over time, a rational, profit-maximizing firm would continually seek to employ managers who accurately minimize costs and continually seek to increase the efficiency of the production process (and hence increase the α_i 's towards one). Nevertheless, the existence of organizational inertia or control problems could cause these cost savings to go unrealized, even in the long run; Porter and van der Linde (1995) include these phenomena in their discussion of sub-optimal firm behavior, along with incomplete information, which has been the focus of the model here.

To better accommodate these long-run concerns and the potential for newer, more efficient production technologies, a dynamic version of the model could be studied. A dynamic modeling of the firm's production and waste disposal problem is left to future research, though it is important to note again that organizational inertia or control problems could still preclude a stable equilibrium. In future research, it would also be useful to study whether an elective menu of environmental policies could also lead to Porter's hypothesis being satisfied but offer a lighter informational burden. For example, the policies could be designed to be incentive-compatible

⁴⁴ This discussion relates to the information required for the government to be certain that the tax will make the firm better off.

such that perfectly profit-maximizing firm managers and behaviorally biased firm managers elect to participate in different policies. Ex-post regulation, the managers with limited attention bias will realize that their costs have decreased as a result of their new input allocation, but the regulatory challenge (and impossibility, perhaps) would be in helping managers realize ex-ante that they are not perfectly cost-minimizing.

APPENDICES

Appendix 1: Chapter 1 Derivation of the Marginal Welfare Effects of the Tax Credit

The optimal tax credit solves:

$$\max_{t_c} V(R, \pi_c, \omega, P_c) = \max_{F, C, x, L} \varphi(u(F, C, x), \bar{L} - L) - \sigma(R) + \lambda(\omega L + \Gamma + \pi_c - P_F F - P_C C - P_x x),$$

subject to:

$$R = F + (\xi - 1)\gamma e \quad (\text{A1.1})$$

$$\pi_c = \pi_c(P_c) \quad (\text{A1.2})$$

$$\omega = w(1 - t_L) \quad (\text{A1.3})$$

$$P_c = e_c \left[\gamma P_G - (1 - \gamma)t + t_c \right] - \frac{e_c w}{e_L} \quad (\text{A1.4})$$

$$\Gamma = t_L w L + t \left[F - e(\gamma - 1) \right] - t_c e. \quad (\text{A1.5})$$

To simplify further computations, we normalize the wage rate to unity, that is, $w = 1$. Totally

differentiating the indirect utility function with respect to t_c , we obtain:

$$\frac{dV}{dt_c} = \frac{\partial V}{\partial R} \frac{dR}{dt_c} + \frac{\partial V}{\partial \pi_c} \frac{d\pi_c}{dt_c} + \frac{\partial V}{\partial \omega} \frac{d\omega}{dt_c} + \frac{\partial V}{\partial P_c} \frac{dP_c}{dt_c} = 0,$$

(A1.6)

where the partial derivatives come from the objective function:

$$\frac{\partial V}{\partial R} = -\sigma'; \frac{\partial V}{\partial \pi_c} = \lambda; \frac{\partial V}{\partial \omega} = \lambda L; \frac{\partial V}{\partial P_c} = -\lambda C, \quad (\text{A1.7})$$

and the total derivatives are obtained from constraints (A1.1–4):

$$\frac{dR}{dt_c} = \frac{dF}{dt_c} + (\xi - 1)\gamma \frac{de}{dt_c}; \frac{d\pi_c}{dt_c} = \pi_c' \frac{dP_c}{dt_c} = C^s e_c; \frac{d\omega}{dt_c} = -\frac{dt_L}{dt_c}; \frac{dP_c}{dt_c} = e_c, \quad (\text{A1.8})$$

where use has been made of Hotelling's lemma, that is, $d\pi_c/dP_c = \pi_c' = C^s$.

Associated with a change in the tax credit is a change in the labor tax such that the real government transfer Γ is constant. To see how the labor tax changes in response to a marginal change in the tax credit, we totally differentiate constraint (A1.5) with respect to t_c to obtain

$$L \frac{dt_L}{dt_c} + t_L \frac{dL}{dt_c} + t \frac{dF}{dt_c} - t(\gamma - 1) \frac{de}{dt_c} - e - t_c \frac{de}{dt_c} = 0. \quad (\text{A1.9})$$

Because we are interested in the effects of the tax credit on the labor market, we need to determine dL/dt_c . To do that, we totally differentiate the labor supply function (the mirror image of the consumer's demand for leisure) with respect to t_c , to obtain⁴⁵

$$\frac{dL}{dt_c} = -\frac{\partial L}{\partial \omega} \frac{dt_L}{dt_c} + e_c \frac{\partial L}{\partial P_C} + e_c C^s \frac{\partial L}{\partial \pi_C}. \quad (\text{A1.10})$$

Substituting the total derivative (A1.10) into (A1.9) and collecting the terms, we arrive at

$$\frac{dt_L}{dt_c} = \frac{t_L e_c \frac{\partial L}{\partial P_C} + t_L e_c C^s \frac{\partial L}{\partial \pi_C} + t \frac{dF}{dt_c} - [t_c + t(\gamma - 1)] \frac{de}{dt_c} - e}{t_L \frac{\partial L}{\partial \omega} - L}. \quad (\text{A1.11})$$

An increase in the labor tax distorts the labor market. The distortion is measured by the marginal excess burden of taxation M defined as the ratio of the increase in the “wedge” distortion (numerator) and the increase in labor tax revenue for a marginal change in the labor tax (denominator). Mathematically,⁴⁶

$$M \equiv \frac{-t_L \frac{\partial L}{\partial t_L}}{L + t_L \frac{\partial L}{\partial t_L}}. \quad (\text{A1.12})$$

By rearranging equation (A1.12), the effect of a change in the nominal labor tax on the labor supply can be expressed as

$$\frac{\partial L}{\partial t_L} = -\frac{ML}{(1 + M)t_L}. \quad (\text{A1.13})$$

⁴⁵ Although the labor supply L depends on ω , Γ , π_C , P_F , P_C , and P_x , a change in the tax credit only affects the labor supply through ω , π_C , P_C .

⁴⁶ Note that because L is measured in hours spent working, each term in equation (A1.12) should be multiplied by the wage rate w to convert the numerator and denominator into dollars terms. The term w cancels out, however, resulting in equation (A1.12).

Alternatively, this effect can be written as

$$\frac{\partial L}{\partial t_L} = \frac{\partial L}{\partial \omega} \frac{\partial \omega}{\partial t_L}. \quad (\text{A1.14})$$

Combining equations (A1.13) and (A1.14) and using the fact that $d\omega/dt_L = -w$ (this follows from equation (A1.3)) yields

$$\frac{\partial L}{\partial \omega} = \frac{ML}{(1+M)t_L}. \quad (\text{A1.15})$$

The derivative (A1.15) describes the response of labor supply to a marginal change in the real wage rate. Substitution of this derivative into equation (A1.11) and rearrangement produce

$$\frac{dt_L}{dt_c} = -(M+1) \frac{t_L e_C \frac{\partial L}{\partial P_C} + t_L e_C C^S \frac{\partial L}{\partial \pi_C} + t \frac{dF}{dt_c} - [t_c + t(\gamma-1)] \frac{de}{dt_c} - e}{L}.$$

(A1.16)

The final optimality condition is obtained by substituting the derivatives (A1.7), (A1.8), and (A1.16) into equation (A1.6) and collecting the terms:

$$\begin{aligned} -\frac{1}{\lambda} \frac{dV}{dt_c} = & - \underbrace{\left[(t-t_c) \frac{de}{dt_c} + t \frac{dG}{dt_c} \right]}_{\text{Primary distortion effect}} \\ & - \underbrace{(M+1)t_L e_C \left(\frac{\partial L}{\partial P_C} + C^S \frac{\partial L}{\partial \pi_C} \right)}_{\text{Tax-interaction effect}} \\ & + \underbrace{M \left[e - (t-t_c) \frac{de}{dt_c} - t \frac{dG}{dt_c} \right]}_{\text{Revenue-recycling effect}} \\ & + \underbrace{\frac{\sigma'}{\lambda} \left(\frac{dG}{dt_c} + \xi \gamma \frac{de}{dt_c} \right)}_{\text{Externality effect}}. \end{aligned} \quad (\text{A1.17})$$

Appendix 2: Chapter 1 Derivation of the Marginal Welfare Effects of the Blend Mandate

The optimal mandate solves:

$$\max_{\theta} V(R, \pi_C, \omega, P_C, P_F) = \max_{F, C, x, L} \varphi(u(F, C, x), \bar{L} - L) - \sigma(R) + \lambda(\omega L + \Gamma + \pi_C - P_F F - P_C C - P_x x),$$

subject to:

$$R = F + (\xi - 1)\gamma e \quad (\text{A2.1})$$

$$\pi_C = \pi_C(P_C) \quad (\text{A2.2})$$

$$\omega = w(1 - t_L) \quad (\text{A2.3})$$

$$P_C = e_C \gamma P_E - \frac{w e_C}{e_L} \quad (\text{A2.4})$$

$$P_F = \theta \left(P_E + \frac{t}{\gamma} - \frac{t_c}{\gamma} \right) + (1 - \theta)(P_G + t) \quad (\text{A2.5})$$

$$\Gamma = t_L w L + t \left[F - e(\gamma - 1) \right] - t_c e \quad (\text{A2.6})$$

$$e = e_C(C^S - C) \quad (\text{A2.7})$$

$$\gamma e = \theta F. \quad (\text{A2.8})$$

Note that under the binding blend mandate, the quantities of ethanol and fuel are linked one-to-one as indicated by equation (A2.8).⁴⁷ After substituting equations (A2.7) and (A2.8) into equations (A2.1), (A2.6), we obtain:

$$R = F + \gamma(\xi - 1)e \text{ and} \quad (\text{A2.1}')$$

$$\Gamma = t_L w L + t F \left[1 - \theta \left(1 - \frac{1}{\gamma} \right) \right] - t_c e. \quad (\text{A2.6}')$$

We normalize the wage rate to unity, $w = 1$. Totally differentiating the indirect utility function with respect to θ yields:

$$\frac{dV}{d\theta} = \frac{\partial V}{\partial R} \frac{dR}{d\theta} + \frac{\partial V}{\partial \pi_C} \frac{d\pi_C}{d\theta} + \frac{\partial V}{\partial \omega} \frac{d\omega}{d\theta} + \frac{\partial V}{\partial P_C} \frac{dP_C}{d\theta} + \frac{\partial V}{\partial P_F} \frac{dP_F}{d\theta}, \quad (\text{A2.9})$$

where the partial derivatives come from the objective function,

⁴⁷ Under the tax credit and exogenous gasoline price (which we assume), the quantities of ethanol and fuel are delinked, however.

$$\frac{\partial V}{\partial R} = -\sigma'; \frac{\partial V}{\partial \pi_c} = \lambda; \frac{\partial V}{\partial \omega} = \lambda L; \frac{\partial V}{\partial P_c} = -\lambda C; \frac{\partial V}{\partial P_f} = -\lambda F, \quad (\text{A2.10})$$

and the total derivatives are obtained from constraints (A2.1') and (A2.2–4):

$$\frac{dR}{d\theta} = \frac{dF}{d\theta} + \gamma(\xi - 1) \frac{de}{d\theta}; \frac{d\pi_c}{d\theta} = C^s \frac{dP_c}{d\theta}; \frac{d\omega}{d\theta} = -\frac{dt_L}{d\theta}; \frac{dP_c}{d\theta} = e_c \gamma \frac{dP_E}{d\theta}. \quad (\text{A2.11})$$

Totally differentiating equation (A2.6') with respect to θ , we obtain

$$-L \frac{dt_L}{d\theta} = t_L \frac{dL}{d\theta} + t \left[1 - \theta \left(1 - \frac{1}{\gamma} \right) \right] \frac{dF}{d\theta} - \left(1 - \frac{1}{\gamma} \right) t F - t_c \frac{de}{d\theta}, \quad (\text{A2.12})$$

where the effect of a change in the blend mandate on the labor supply in the economy can be decomposed, similarly to equation (A1.10), as follows:

$$\frac{dL}{d\theta} = -\frac{\partial L}{\partial \omega} \frac{dt_L}{d\theta} + \frac{\partial L}{\partial P_c} \frac{dP_c}{d\theta} + C^s \frac{\partial L}{\partial \pi_c} \frac{dP_c}{d\theta} + \frac{\partial L}{\partial P_f} \frac{dP_f}{d\theta}. \quad (\text{A2.13})$$

Substituting equation (A2.13) into (A2.12), invoking equation (A1.15), and rearranging, we get

$$\frac{dt_L}{d\theta} = -(1+M) \frac{t_L \left(\frac{\partial L}{\partial P_c} + C^s \frac{\partial L}{\partial \pi_c} \right) \frac{dP_c}{d\theta} + t_L \frac{\partial L}{\partial P_f} \frac{dP_f}{d\theta} + t \left[1 - \theta \left(1 - \frac{1}{\gamma} \right) \right] \frac{dF}{d\theta} - \left(1 - \frac{1}{\gamma} \right) t F - t_c \frac{de}{d\theta}}{L}. \quad (\text{A2.14})$$

Finally, the optimality condition for a blend mandate is derived by substituting the derivatives (A2.10), (A2.11), and (A2.14) into equation (A2.9) and collecting the terms:

$$\begin{aligned}
-\frac{1}{\lambda} \frac{dV}{d\theta} = & \underbrace{\left[F \frac{dP_F}{d\theta} - e\gamma \frac{dP_E}{d\theta} + t \left(1 - \frac{1}{\gamma} \right) \left(F + \theta \frac{dF}{d\theta} \right) - t \frac{dF}{d\theta} + t_c \frac{de}{d\theta} \right]}_{\text{Primary distortion effect}} \\
& - \underbrace{(1+M)t_L \left[\left(\frac{\partial L}{\partial P_C} + C^S \frac{\partial L}{\partial \pi_C} \right) \frac{dP_C}{d\theta} + \frac{\partial L}{\partial P_F} \frac{dP_F}{d\theta} \right]}_{\text{Tax interaction effect}} \\
& + \underbrace{M \left\{ t \left(1 - \frac{1}{\gamma} \right) \left(F + \theta \frac{dF}{d\theta} \right) - t \frac{dF}{d\theta} + t_c \frac{de}{d\theta} \right\}}_{\text{Revenue recycling effect}} \\
& + \underbrace{\frac{\sigma'}{\lambda} \left(\frac{dF}{d\theta} + \gamma(\xi - 1) \frac{de}{d\theta} \right)}_{\text{Externality effect}}.
\end{aligned} \tag{A2.15}$$

Appendix 3: Chapter 1 Derivation of the Marginal Welfare Effects of the Tax Credit with a Binding Blend Mandate

The tax credit solves:

$$\max_{t_c} V(R, \pi_C, \omega, P_C, P_F) = \max_{F, C, x, L} \varphi(u(F, C, x), \bar{L} - L) - \sigma(R) + \lambda(\omega L + \Gamma + \pi_C - P_F F - P_C C - P_x x),$$

subject to:

$$R = F + (\xi - 1)\gamma e \tag{A3.1}$$

$$\pi_C = \pi_C(P_C) \tag{A3.2}$$

$$\omega = w(1 - t_L) \tag{A3.3}$$

$$P_C = e_C \gamma P_E - \frac{w e_C}{e_L} \tag{A3.4}$$

$$P_F = \theta \left(P_E + \frac{t}{\gamma} - \frac{t_c}{\gamma} \right) + (1 - \theta)(P_G + t) \tag{A3.5}$$

$$\Gamma = t_L w L + t \left[F - e(\gamma - 1) \right] - t_c e \tag{A3.6}$$

$$e = e_C(C^S - C) \tag{A3.7}$$

$$\gamma e = \theta F. \tag{A3.8}$$

After substituting equations (A3.7) and (A3.8) into equations (A3.1), (A3.6), we obtain:

$$R = F + \gamma(\xi - 1)e \text{ and} \tag{A3.1'}$$

$$\Gamma = t_L w L + t F \left[1 - \theta \left(1 - \frac{1}{\gamma} \right) \right] - t_c e. \tag{A3.6'}$$

We normalize the wage rate such that $w = 1$. Totally differentiating the indirect utility function with respect to t_c yields:

$$\frac{dV}{dt_c} = \frac{\partial V}{\partial R} \frac{dR}{dt_c} + \frac{\partial V}{\partial \pi_c} \frac{d\pi_c}{dt_c} + \frac{\partial V}{\partial \omega} \frac{d\omega}{dt_c} + \frac{\partial V}{\partial P_c} \frac{dP_c}{dt_c} + \frac{\partial V}{\partial P_F} \frac{dP_F}{dt_c}, \quad (\text{A3.9})$$

where the partial derivatives come from the objective function,

$$\frac{\partial V}{\partial R} = -\sigma'; \frac{\partial V}{\partial \pi_c} = \lambda; \frac{\partial V}{\partial \omega} = \lambda L; \frac{\partial V}{\partial P_c} = -\lambda C; \frac{\partial V}{\partial P_F} = -\lambda F, \quad (\text{A3.10})$$

and the total derivatives are obtained from constraints (A3.1') and (A3.2–4):

$$\frac{dR}{dt_c} = \frac{dF}{dt_c} + \gamma(\xi - 1) \frac{de}{dt_c}; \frac{d\pi_c}{dt_c} = C^s \frac{dP_c}{dt_c}; \frac{d\omega}{dt_c} = -\frac{dt_L}{dt_c}; \frac{dP_c}{dt_c} = e_c \gamma \frac{dP_E}{dt_c}. \quad (\text{A3.11})$$

Totally differentiating equation (A3.6') with respect to t_c , we obtain

$$-L \frac{dt_L}{dt_c} = t_L \frac{dL}{dt_c} + t \left[1 - \theta \left(1 - \frac{1}{\gamma} \right) \right] \frac{dF}{dt_c} - e - t_c \frac{de}{dt_c}, \quad (\text{A3.12})$$

where the effect of a change in the tax credit on the labor supply in the economy is:

$$\frac{dL}{dt_c} = -\frac{\partial L}{\partial \omega} \frac{dt_L}{dt_c} + \frac{\partial L}{\partial P_c} \frac{dP_c}{dt_c} + C^s \frac{\partial L}{\partial \pi_c} \frac{dP_c}{dt_c} + \frac{\partial L}{\partial P_F} \frac{dP_F}{dt_c}. \quad (\text{A3.13})$$

Substituting equation (A3.13) into (A3.12), invoking equation (A1.15), and rearranging, obtains

$$\frac{dt_L}{dt_c} = -(1 + M) \frac{t_L \left(\frac{\partial L}{\partial P_c} + C^s \frac{\partial L}{\partial \pi_c} \right) \frac{dP_c}{dt_c} + t_L \frac{\partial L}{\partial P_F} \frac{dP_F}{dt_c} + t \left[1 - \theta \left(1 - \frac{1}{\gamma} \right) \right] \frac{dF}{dt_c} - e - t_c \frac{de}{dt_c}}{L}. \quad (\text{A3.14})$$

Finally, the optimality condition for a blend mandate is derived by substituting the derivatives (A3.10), (A3.11), and (A3.14) into equation (A3.9) and collecting the terms:

$$\begin{aligned}
-\frac{1}{\lambda} \frac{dV}{dt_c} = & \underbrace{\left\{ F \frac{dP_F}{dt_c} - e\gamma \frac{dP_E}{dt_c} + e + t_c \frac{de}{dt_c} - t \left[1 - \theta \left(1 - \frac{1}{\gamma} \right) \right] \frac{dF}{dt_c} \right\}}_{\text{Primary distortion effect}} \\
& - \underbrace{(1+M)t_L \left[\left(\frac{\partial L}{\partial P_C} + C^S \frac{\partial L}{\partial \pi_C} \right) \frac{dP_C}{dt_c} + \frac{\partial L}{\partial P_F} \frac{dP_F}{dt_c} \right]}_{\text{Tax interaction effect}} \\
& + \underbrace{M \left\{ e + t_c \frac{de}{dt_c} - t \left[1 - \theta \left(1 - \frac{1}{\gamma} \right) \right] \frac{dF}{dt_c} \right\}}_{\text{Revenue recycling effect}} \\
& + \underbrace{\frac{\sigma'}{\lambda} \left(\frac{dF}{dt_c} + \gamma(\xi - 1) \frac{de}{dt_c} \right)}_{\text{Externality effect}}.
\end{aligned} \tag{A3.15}$$

Appendix 4: Chapter 1 Derivations for the Numerical Model

The utility-maximizing demand functions can be found in two stages. We first focus on the inner nest of the utility function. Here, minimization of total expenditures on fuel, corn, and the numeraire good, subject to $X = 1$, yields the proportions of individual consumption goods in one unit of the composite good X .⁴⁸ These proportions are constant with respect to the level of X and are denoted by $b_F = F/X$, $b_C = C/X$, and $b_x = x/X$, respectively. Thus, the first-stage problem is:⁴⁹

$$\min_{F, C, x} P_F F + P_C C + P_x x,$$

subject to:

$$\sigma_X \left(\alpha_F F^{\frac{\delta_x - 1}{\delta_x}} + \alpha_C C^{\frac{\delta_x - 1}{\delta_x}} + (1 - \alpha_F - \alpha_C) x^{\frac{\delta_x - 1}{\delta_x}} \right)^{\frac{\delta_x}{\delta_x - 1}} = 1,$$

⁴⁸ That is, how much of fuel, corn, and the numeraire good is needed to produce one unit of the composite good at a minimum cost.

⁴⁹ Note that for $X = 1$, $b_F = F$, $b_C = C$, and $b_x = x$.

resulting in the following demand functions (proportions) for $X = 1$:

$$b_F = \left(\alpha_F + \alpha_C \left(\frac{\alpha_F}{\alpha_C} \frac{P_C}{P_F} \right)^{1-\delta_x} + (1-\alpha_F-\alpha_C) \left(\frac{\alpha_F}{(1-\alpha_F-\alpha_C)} \frac{P_x}{P_F} \right)^{1-\delta_x} \right)^{\frac{\delta_x}{1-\delta_x}} \frac{1}{\sigma_X};$$

$$b_C = \left(\alpha_C + \alpha_F \left(\frac{\alpha_C}{\alpha_F} \frac{P_F}{P_C} \right)^{1-\delta_x} + (1-\alpha_F-\alpha_C) \left(\frac{\alpha_C}{(1-\alpha_F-\alpha_C)} \frac{P_x}{P_C} \right)^{1-\delta_x} \right)^{\frac{\delta_x}{1-\delta_x}} \frac{1}{\sigma_X};$$

$$b_x = \left((1-\alpha_F-\alpha_C) + \alpha_F \left(\frac{(1-\alpha_F-\alpha_C)}{\alpha_F} \frac{P_F}{P_x} \right)^{1-\delta_x} + \alpha_C \left(\frac{(1-\alpha_F-\alpha_C)}{\alpha_C} \frac{P_C}{P_x} \right)^{1-\delta_x} \right)^{\frac{\delta_x}{1-\delta_x}} \frac{1}{\sigma_X}.$$

The optimal demands from the first stage provide the price index P_X (price of the aggregate consumption good X), defined as

$$P_X = b_F P_F + b_C P_C + b_x P_x.$$

The second-stage is utility maximization (outer nest) between leisure and the composite consumption good⁵⁰:

$$\max_{N, X} U = \left(\alpha_N N^{\frac{\delta-1}{\delta}} + (1-\alpha_N) X^{\frac{\delta-1}{\delta}} \right)^{\frac{\delta}{\delta-1}} - \sigma(R),$$

subject to:

$$P_X X + w(1-t_L)N = w(1-t_L)\bar{L} + P_X \Gamma + \pi_C,$$

resulting in demand for leisure and the composite good:

$$N = \frac{w(1-t_L)\bar{L} + P_X \Gamma + \pi_C}{P_X^{1-\delta} \left(\frac{w(1-t_L)(1-\alpha_N)}{\alpha_N} \right)^{\delta} + w(1-t_L)} \quad \text{and} \quad X = \left(\frac{w(1-t_L)(1-\alpha_N)}{\alpha_N P_X} \right)^{\delta} N.$$

⁵⁰ Recall that the consumer sees the level of the externality R as exogenous and thus does not take it into consideration when choosing his optimal consumption bundle.

Appendix 5: Chapter 1 Determination of the Time-Endowment Ratio

We follow Ballard (2000) to determine the time-endowment ratio Φ (i.e., the representative consumer's endowment of time divided by the amount of labor that is supplied in the baseline) that is consistent with uncompensated price and income labor-supply elasticities found in the literature. Because the utility function used in this essay differs from that in Ballard (2000), below we rederive the calibration procedure.

The representative consumer maximizes his utility, subject to the budget constraint:

$$\max U = \left(\alpha_N N^{\frac{\delta-1}{\delta}} + (1-\alpha_N) X^{\frac{\delta-1}{\delta}} \right)^{\frac{\delta}{\delta-1}},$$

subject to:

$$P_X X + \omega N = \omega \bar{L} + REV + \pi_C,$$

where $\omega = w(1-t_L)$.

The resulting demands for leisure N and the composite consumption good X are:

$$N = \frac{\alpha_N^\delta (\omega \bar{L} + REV + \pi_C)}{\omega (P_X^{1-\delta} \omega^{\delta-1} (1-\alpha_N)^\delta + \alpha_N^\delta)} \quad \text{and} \quad X = \left[\frac{\omega (1-\alpha_N)}{P_X \alpha_N} \right]^\delta N.$$

The uncompensated leisure-demand elasticity η_N is

$$\eta_N = \frac{\partial N}{\partial \omega} \frac{\omega}{N} = \frac{\alpha_N^\delta \bar{L} \left[\omega (P_X^{1-\delta} \omega^{\delta-1} (1-\alpha_N)^\delta + \alpha_N^\delta) \right] - \left[\alpha_N^\delta (\omega \bar{L} + REV + \pi_C) \right] \left[(P_X^{1-\delta} \omega^{\delta-1} (1-\alpha_N)^\delta + \alpha_N^\delta) + (\delta-1) P_X^{1-\delta} \omega^{\delta-1} (1-\alpha_N)^\delta \right]}{N \omega (P_X^{1-\delta} \omega^{\delta-1} (1-\alpha_N)^\delta + \alpha_N^\delta)^2}.$$

Denote $\Delta = P_X^{1-\delta} \omega^{\delta-1} (1-\alpha_N)^\delta + \alpha_N^\delta$, then

$$\eta_N = \frac{\alpha_N^\delta \bar{L}}{\Delta N} - \frac{\alpha_N^\delta (\omega \bar{L} + REV + \pi_C) [\Delta \delta - (\delta-1) \alpha_N^\delta]}{N \omega \Delta^2}. \quad (\text{A5.1})$$

Rearranging the leisure demand function, we obtain

$$\frac{\alpha_N^\delta}{\Delta} = \frac{N \omega}{\omega \bar{L} + REV + \pi_C}, \quad (\text{A5.2})$$

and substituting into equation (5.1), we arrive at

$$\eta_N = \frac{\omega \bar{L}}{\omega \bar{L} + REV + \pi_C} - \delta - (1 - \delta) \frac{\alpha_N^\delta}{\Delta}. \quad (\text{A5.3})$$

The relationship between uncompensated and compensated labor supply elasticity is (see Ballard, 2000)

$$\eta_N = -\frac{\eta_L}{\Phi - 1}. \quad (\text{A5.4})$$

Solving equations (A5.3) and (A5.4) for δ and α_N , we obtain

$$\delta = \frac{1}{1 + (REV + \pi_C)/\omega L} + \frac{\eta_L}{\Phi - 1} \left(\frac{\Phi + (REV + \pi_C)/\omega L}{1 + (REV + \pi_C)/\omega L} \right) \text{ and } \alpha_N = \left\{ \left[\frac{\omega L + REV + \pi_C}{(\Phi - 1) P_X^{1-\delta} \omega^\delta L} \right]^{\frac{1}{\delta}} + 1 \right\}^{-1}.$$

The indirect utility function corresponding to the consumer's utility maximization problem above is

$$V = (\omega \bar{L} + REV + \pi_C) \omega^{-1} \left[P_X^{1-\delta} \omega^{\delta-1} (1 - \alpha_N)^\delta + \alpha_N^\delta \right]^{\frac{1}{\delta-1}}, \quad (\text{A5.5})$$

and the expenditure function is given by

$$E^* = V \omega \left[P_X^{1-\delta} \omega^{\delta-1} (1 - \alpha_N)^\delta + \alpha_N^\delta \right]^{\frac{1}{1-\delta}}. \quad (\text{A5.6})$$

By Shepard's Lemma, we have $\partial E^*/\partial \omega = N^* = V \alpha_N^\delta \left[P_X^{1-\delta} \omega^{\delta-1} (1 - \alpha_N)^\delta + \alpha_N^\delta \right]^{\frac{\delta}{1-\delta}}$, and the

Slutsky derivative is $\partial N^*/\partial \omega = -V \alpha_N^\delta (1 - \alpha_N)^\delta \delta \Delta^{\frac{2\delta-1}{1-\delta}} P_X^{1-\delta} \omega^{\delta-2}$, from which for the compensated leisure supply elasticity we have

$$\eta_N^* = -\frac{\delta (1 - \alpha_N)^\delta P_X^{1-\delta} \omega^{\delta-1}}{\Delta}. \quad (\text{A5.7})$$

The relation between compensated elasticities for labor and leisure supply is given by

$$\eta_L^* = (1 - \Phi) \eta_N^*. \quad (\text{A5.8})$$

Because by the Slutsky decomposition the difference between the compensated and uncompensated labor supply elasticities is equal to the absolute value of the total-income elasticity of labor supply (Ballard, 2000), the closing condition for our calibration is

$$\eta_L - \eta_L^* = |\eta_I|. \quad (\text{A5.9})$$

which implicitly solves for the time-endowment ratio Φ .

Appendix 6: Chapter 1 Supplementary Tables

Table A1. Data Used to Calibrate the Model

Variable/parameter	Symbol	Value	Unit	Source
PARAMETERS				
Carbon emissions of corn ethanol relative to gasoline	ξ	0.80		de Gorter and Just (2010)
Miles per gallon of ethanol relative to gasoline	γ	0.70		de Gorter and Just (2010)
Ethanol produced from one bushel of corn	β	2.80	gallon/bushel	Eidman (2007)
DDGS production coefficient ^a	μ	17/56		Eidman (2007)
Price of DDGS relative to corn price	r	0.86		$r = (P_{DDGS} * 56) / (P_C * 2000)$
Share of DDGS in one bushel of corn	δ_C	0.26		$\delta_C = r * \mu$
Marginal product of corn in ethanol production	e_C	3.78	gallon/bushel	$\beta / (1 - \delta_C)$
Marginal product of labor in ethanol production	e_L	1.25	gallon/hour	$e_C * w / (e_C * P_C - P_C)$
Marginal external cost of CO ₂ emissions ^b	MEC	0.06	\$/gallon	Parry and Small (2005)
Share parameter of fuel consumption in utility	α_F	2.89E-06		Calibrated using equation for b_F in Appendix 4
Share parameter of corn consumption in utility	α_C	9.63E-10		Calibrated using equation for b_C in Appendix 4
Scale factor on composite consumption good in utility	σ_X	1.06		Calibrated using the constraint in Appendix 4
Labor endowment as proportion of labor	Φ	1.19		Appendix 5
Share parameter of leisure consumption in utility	α_N	0.13		Appendix 5
Returns to scale in corn production	ε^S	0.23		$\varepsilon^{CS} / (\varepsilon^{CS} + 1)$
Labor share of income	ρ	0.57		U.S. Bureau of Economic Analysis ^c
Marginal product of labor in numeraire production	k	1.00		$k = w / P_x$
Scale parameter for the corn production function	A	7.50		$A = C^{S \wedge} (1 - \varepsilon^S) / (\varepsilon^S * P_C / w)^{\wedge} \varepsilon^S$
Marginal product of labor in gasoline production	B	0.57		$B = w / P_G$
POLICY VARIABLES				
Ethanol tax credit	t_c	0.50	\$/gallon	$t_c = \$0.45/\text{gal} + \$0.048/\text{gal}$ ^d
Blend mandate (energy equivalent)	θ	0.06		$\theta = E/F$
Fuel tax	t	0.49	\$/gallon	American Petroleum Institute ^e
Labor tax (ad valorem)	t_L	0.40		Goulder et al. (1999)
After-tax wage	ω	0.60		$\omega = w * (1 - t_L)$
PRICES				
Wage	w	1.00	\$/hour	Normalized
Price of the numeraire good	P_x	1.00		Normalized
Price of the composite good	P_X	1.00		Normalized to unity in the baseline
Gasoline price	P_G	1.76	\$/gallon	Gasoline average rack price in Omaha, Nebraska ^f
Ethanol price (volumetric)	P_e	1.79	\$/gallon	Ethanol average rack price in Omaha, Nebraska ^f
Ethanol price (energy)	P_E	2.56	\$/GEEG	$P_E = P_e / \gamma$
Fuel price	P_F	2.27	\$/GEEG	$P_F = \theta * (P_E + t / \gamma - t_c / \gamma) + (1 - \theta) * (P_G + t)$
Corn market price	P_C	3.75	\$/bushel	USDA ^g
DDGS price	P_{DDGS}	114.40	\$/ton	USDA ^h

Notes:

^a DDGS = Dried distillers grains with solubles

^b Corresponds to \$25/tonne carbon

^c <http://www.bea.gov/national/index.htm#gdp>

^d \$0.45/gallon is the federal component of the tax credit; the \$0.048/gallon is the average state tax credit reported by Koplow (2009).

^e <http://www.api.org/statistics/fueltaxes/upload/gasoline-diesel-summary.pdf> (average for 2009)

^f <http://www.neo.ne.gov/stathtml/66.html>

^g <http://www.ers.usda.gov/data-products/feed-grains-database/feed-grains-yearbook-tables.aspx>

^h <http://www.ers.usda.gov/data-products/feed-grains-database/feed-grains-yearbook-tables.aspx#26818>

Appendix A1. Data Used to Calibrate the Model (continued)

Variable/parameter	Symbol	Value	Unit	Source
QUANTITIES				
U.S. gross domestic product	GDP	13939.00	billion dollars	U.S. Bureau of Economic Analysis ^c
Time endowment	L^-	9434.96	billion hours	$L^- = \Phi L$
Labor supply	L	7945.23	billion hours	$\rho * GDP/w$
Leisure demand	N	1489.73	billion hours	$N = L^- - L$
Labor used in gasoline production	L_G	217.74	billion hours	$L_G = G/B$
Labor used in ethanol production	L_e	8.83	billion hours	$L_e = e/e_L$
Labor used in corn production	L_C	11.36	billion hours	$L_C = (w/(\epsilon^S * A * P_C))^{1/(\epsilon^S - 1)}$
Labor used in numeraire production	L_x	7707.30	billion hours	$L_x = L - L_e - L_C - L_G$
Nominal government revenue	REV	3238.65	billion dollars	$REV = w * t_L * L + t * f - t_c * e$
Real government transfer	Γ	3238.65	billion dollars	REV/P_X
Gasoline supply	G	123.71	billion gallons	$G = f - e$
Ethanol consumption (volumetric)	e	11.04	billion gallons	EIA ⁱ
Ethanol consumption (energy)	E	7.73	billion GEEGs	$E = \gamma * e$
Fuel consumption (volumetric)	f	134.75	billion gallons	EIA ⁱ
Fuel consumption (energy)	F	131.44	billion GEEGs	$F = G + E$
Corn supply	C^S	13.15	billion bushels	USDA ^j
Non-ethanol corn consumption	C	10.23	billion bushels	$C = C^S - C^e$
Corn used for ethanol production	C^e	2.92	billion bushels	$C^e = e/e_C$
Numeraire consumption	x	7707.30		$x = kL_x$
Composite good consumption	X	8040.58		$X = N * (\omega * (1 - \alpha_N) / (\alpha_N * P_X))^{\delta}$
Profits in corn production	π_C	37.88	billion dollars	$P_C * C^S - w * L_C$
Externality	R	129.89		$R = G + \xi E$
ELASTICITIES				
Elasticity of corn supply	ϵ^{CS}	0.30		Cui et al. (2011)
Income elasticity of labor supply	ϵ^{LI}	-0.10		Ballard (2000)
Uncompensated elasticity of labor supply	ϵ^{LL}	0.10		Ballard (2000)
Elasticity of substitution between leisure and consumption	δ	1.19		Appendix 5
Elasticity of substitution among consumption goods	δ_X	0.30		Chosen to correspond to elasticities of demand for fuel and corn from the literature.

Notes:

ⁱ <http://www.eia.gov/forecasts/steo/query/>

^j <http://www.ers.usda.gov/Data/FeedGrains/FeedYearbook.aspx> (Table 4)

Table A2. Description of Market Equilibrium with Alternate Policy Scenarios

	Status Quo	Tax Credit Removed	No Ethanol Policies
Ethanol tax credit (\$/gallon)	0.498	0.000	0.000
Blend mandate (%), energy equivalent	5.88	5.88	0.00
Fuel tax (\$/gallon)	0.490	0.490	0.490
Fuel price (\$/GEEG)	2.268	2.309	2.250
Ethanol price (\$/GEEG)	2.557	2.554	N/A
Corn price (\$/bushel)	3.745	3.738	2.468
Labor tax rate	0.4000	0.3996	0.3983
Fuel quantity (billion gallons)	134.75	134.04	131.84
Fuel quantity (billion GEEGs)	131.44	130.74	131.84
Gasoline quantity (billion gallons)	123.71	123.06	131.84
Ethanol quantity (billion gallons)	11.038	10.979	0.000
Corn quantity (billion bushels)	10.232	10.239	11.604
Total corn supply (billion bushels)	13.150	13.142	11.604
Labor supply (billion hours)	7945.2	7945.2	7951.6
Price level	1.000	1.001	0.998
Net fuel tax revenue (\$ billion)	61	66	65
Total government revenue (\$ billion)	3239	3241	3232
Total emissions*	129.89	129.21	131.84

* Emissions units are defined such that 1 gallon gasoline = 1 unit of emissions

N/A: "Not applicable"

Source: calculated

Table A3. Description of Market Equilibria for Table 3 Scenarios

Pre-existing distortion(s) Policy description	Fuel tax and labor tax			Fuel tax			Labor tax		
	Mandate	Equivalent tax credit	No ethanol policy	Mandate	Equivalent tax credit	No ethanol policy	Mandate	Equivalent tax credit	No ethanol policy
Ethanol tax credit (\$/gallon)	0.000	0.703	0.000	0.000	0.850	0.000	0.000	0.583	0.000
Fuel tax (\$/gallon)	0.49	0.49	0.49	0.49	0.49	0.49	0.00	0.00	0.00
Fuel price (\$/GEEG)	2.31	2.25	2.25	2.32	2.25	2.25	1.81	1.76	1.76
Ethanol price (\$/GEEG)	2.55	2.55	N/A	2.76	2.76	N/A	2.59	2.59	N/A
Corn price (\$/bushel)	3.74	3.74	2.47	4.29	4.29	2.79	3.84	3.84	2.46
Labor tax rate	0.3996	0.4001	0.3983	0.0	0.0	0.0	0.4045	0.4050	0.4031
Fuel quantity (billion gallons)	134.0	135.0	131.8	144.1	145.4	141.9	143.9	145.0	141.6
Fuel quantity (billion GEEGs)	130.7	131.7	131.8	140.6	141.9	141.9	140.4	141.5	141.6
Gasoline quantity (billion gallons)	123.1	124.1	131.8	132.3	133.6	141.9	132.1	133.2	141.6
Ethanol quantity (billion gallons)	10.98	10.98	0.00	11.81	11.81	0.00	11.79	11.79	0.00
Corn quantity (billion bushels)	10.24	10.24	11.60	10.58	10.58	12.04	10.13	10.13	11.59
Total corn supply (billion bushels)	13.14	13.14	11.60	13.70	13.70	12.04	13.25	13.25	11.59
Labor supply (billion hours)	7945	7945	7952	8558	8559	8560	7945	7945	7952
Price level	1.0007	0.9997	0.9980	1.0016	1.0004	0.9984	0.9924	0.9915	0.9897
Net fuel tax revenue (\$ billion)	66	58	65	71	61	70	0	-7	0
Government revenue (\$ billion)	3241	3238	3232	70.65	61.26	69.57	3214	3211	3205
Total emissions**	129.2	130.2	131.8	138.9	140.2	141.9	138.7	139.8	141.6
Welfare change from policy removal (\$ billion)	7.096	6.607	N/A	6.296	5.693	N/A	7.227	7.269	N/A

* 5.88 percent (energy equivalent)

** Emissions units are defined such that 1 gallon gasoline = 1 unit of emissions

N/A: "Not applicable"

Source: calculated

Appendix 7: Chapter 2 Theoretical Model Derivations

Solution of equilibrium if the durable good is not visible ($a = 0$)

The consumer's maximization problem is:

$$\max_{A, Q, W} U(A, Q, W) = -\beta_A \ln A + \beta_Q \ln Q + \beta_W \ln W + \beta_x \ln \left(y - zc(Q) \frac{W}{2A-1} \right),$$

where $c(Q) = \delta_1 e^{\delta_2 Q}$.

The first-order conditions for an interior equilibrium are given by:

$$D(A, W) = -\beta_A \ln A + \beta_W \ln W + \beta_{AW} \ln W \ln \left(\frac{1}{2A-1} \right)$$

$$D_A = -\frac{\beta_A}{A} - \beta_{AW} \frac{W}{2A-1} \frac{2W}{(2A-1)^2} = -\frac{\beta_A}{A} - \frac{2\beta_{AW}}{2A-1}$$

$$\rightarrow \frac{\alpha_A}{\alpha_W} (-A)^{-\frac{1}{\delta_D}} = \frac{2}{2A-1} W^{\frac{\delta_D-1}{\delta_D}}$$

$$W = \left(\frac{\alpha_Q}{\alpha_W \delta_2} \right)^{\frac{\delta_D}{\delta_D-1}} Q^{-\frac{1}{\delta_D-1}}$$

Dividing the first-order conditions of A and Q by the first-order condition for W yields analytical expressions for A and Q :

$$\frac{W}{A} = \frac{\left(\frac{2W}{(2A-1)^2} \right) \beta_W}{\left(\frac{1}{2A-1} \right) \beta_A} = \frac{2W}{(2A-1)} \frac{\beta_W}{\beta_A} \rightarrow 2A \left(1 - \frac{\beta_W}{\beta_A} \right) = 1 \rightarrow A = \frac{\beta_A}{2(\beta_A - \beta_W)};$$

$$\frac{W}{Q} = \frac{\left(\frac{W}{2A-1} \right) c'(Q) \beta_W}{\left(\frac{1}{2A-1} \right) c(Q) \beta_Q} = W \frac{c'(Q) \beta_W}{c(Q) \beta_Q} \rightarrow Q = \frac{c(Q) \beta_Q}{c'(Q) \beta_W} = \frac{\beta_Q}{\delta_2 \beta_W}.$$

I assume that $\beta_A > \beta_W$ so that A is defined and greater than zero. The expressions for A and Q can be plugged into the first-order condition for W to obtain an explicit expression for W :

$$W = y \frac{\beta_W^2}{zc(Q)(\beta_x + \beta_W)(\beta_A - \beta_W) \delta_1 \exp \left(\frac{\beta_Q}{\beta_W} \right)}.$$

Solution of equilibrium if the durable good is visible, $a > 0$, and $D_V = A$

The consumer's maximization problem is:

$$\max_{A,Q,W} U(A,Q,W) = (1-a) \left(-\beta_A \ln A + \beta_Q \ln Q + \beta_W \ln W + \beta_x \ln \left(y - zc(Q) \frac{W}{2A-1} \right) \right) \\ + a \left(-\beta_A \ln A + \beta_Q \ln Q + \beta_W \ln W + \beta_x \ln (g(A)) \right)$$

Note that since A is an inferior good (it reflects the opposite of newness), $g(A)$ will be a decreasing function. The first-order conditions for an interior equilibrium are:

$$(A): -\frac{\beta_A}{A} + (1-a) \frac{\beta_x zc(Q)}{y - z \frac{W}{2A-1}} \left(\frac{2W}{(2A-1)^2} \right) + a \frac{\beta_x}{g(A)} g'(A) = 0;$$

$$\rightarrow g'(A) = \frac{g(A)}{a\beta_x} \left(\frac{\beta_A}{A} - (1-a) \frac{\beta_x zc(Q)}{y - z \frac{W}{2A-1}} \left(\frac{2W}{(2A-1)^2} \right) \right);$$

$$(Q): \frac{\beta_Q}{Q} = (1-a) \frac{\beta_x zW}{y - z \frac{W}{2A-1}} \left(\frac{c'(Q)}{2A-1} \right);$$

$$(W): \frac{\beta_W}{W} = (1-a) \frac{\beta_x zc(Q)}{y - z \frac{W}{2A-1}} \left(\frac{1}{2A-1} \right).$$

Dividing the first-order condition of Q by that of W yields the same implicit function for q as in the $a = 0$ equilibrium:

$$\frac{W}{Q} = \frac{Wc'(Q)}{c(Q)} \frac{\beta_W}{\beta_Q} \rightarrow Q = \frac{c(Q)}{c'(Q)} \frac{\beta_Q}{\beta_W}.$$

Re-arranging the first-order condition for W yields an expression that can be plugged into the first-order equation for A . After substituting this expression, the F.O.C. for A can be re-arranged to solve for the derivative of the signaling function, $g'(A)$:

$$FOC(W) \rightarrow \frac{\beta_W}{W} (2A-1) = (1-a) \frac{\beta_x zc(Q)}{y - z \frac{W}{2A-1}}; \\ \rightarrow g'(A) = g(A) \left(-\frac{2\beta_W}{a\beta_x} \frac{1}{2A-1} + \frac{\beta_A}{a\beta_x} \frac{1}{A} \right).$$

In order for the signaling equilibrium to exist, we must have $g'(A) < 0$ so that an older durable good stock is associated with lower x consumption. This requires:

$$g'(A) < 0 \Leftrightarrow \frac{2\beta_w}{(2A-1)} > \frac{\beta_A}{A} \Leftrightarrow A < \frac{\beta_A}{2(\beta_A - \beta_w)}.$$

Note that this A is the same as the no-social effects optimum. This means that the signaling distortion causes all income types above the lowest type to increase their stock's newness above the no-social effects optimum.

The general solution to the differential equation $g'(A)$ can be solved using separation of variables:

$$g'(A) = g(A) \left(\frac{K}{2A-1} + \frac{J}{A} \right);$$

$$K \equiv -\frac{2\beta_w}{a\beta_x}; J \equiv \frac{\beta_A}{a\beta_x};$$

$$Y \equiv g(A) \rightarrow \frac{dY}{dA} = Y \left(\frac{K}{2A-1} + \frac{J}{A} \right).$$

$$\frac{1}{Y} dY = \left(\frac{K}{2A-1} + \frac{J}{A} \right) dA;$$

$$\ln Y = \frac{1}{2} K \ln(2A-1) + J \ln A + \bar{C};$$

$$\rightarrow g(A) = (2A-1)^{\frac{K}{2}} A^J \exp(\bar{C});$$

$$g(A) = (2A-1)^{-\frac{\beta_w}{a\beta_x}} A^{\frac{\beta_A}{a\beta_x}} C, C \equiv \exp(\bar{C}).$$

To pin down the constant of integration C in $g(A)$, consider the actions of the lowest-income type consumer with $y = \underline{y}$. Since she cannot improve her status by signaling, her actions in the signaling game will match those of the non-signaling equilibrium.

We can plug the demand functions from the $a = 0$ equilibrium into her budget constraint and make use of the equilibrium condition that $g(A) = x$ to solve for the constant of integration, C :

$$\begin{aligned}
A &= \frac{\beta_A}{2(\beta_A - \beta_W)}; W = y \frac{\beta_W^2}{zc(Q)(\beta_x + \beta_W)(\beta_A - \beta_W)}; \\
x &= y - zc(Q) \frac{W}{2A-1} = y \left(1 - \frac{\beta_W}{\beta_x + \beta_W} \right); \\
g(A) &= \left(\frac{\beta_W}{\beta_A - \beta_W} \right)^{\frac{\beta_W}{a\beta_x}} \left(\frac{\beta_A}{2(\beta_A - \beta_W)} \right)^{\frac{\beta_A}{a\beta_x}} C = (\beta_A - \beta_W)^{-\left(\frac{\beta_A - \beta_W}{a\beta_x}\right)} (\beta_W)^{-\frac{\beta_W}{a\beta_x}} \left(\frac{\beta_A}{2} \right)^{\frac{\beta_A}{a\beta_x}} C; \\
g(A) = x &\rightarrow C = y \left(\frac{\beta_x}{\beta_x + \beta_W} \right) \left(\left(\frac{\beta_A}{2} \right)^{-\beta_A} (\beta_W)^{\beta_W} (\beta_A - \beta_W)^{\beta_A - \beta_W} \right)^{\frac{1}{a\beta_x}} > 0.
\end{aligned}$$

Given the function $g(A)$ and the equilibrium condition that $g(A) = x$, we can plug in $g(A)$ for x in the budget constraint and make use of the expression for W in terms of $(2A - 1)$ to derive an implicit function that defines demand for A in this $a > 0$ equilibrium:

$$\begin{aligned}
y &= x + zc(Q) \frac{W}{2A-1}; \\
\frac{W}{2A-1} &= \frac{y\beta_W}{z((1-a)\beta_x c(Q) + \beta_W)}; \\
\rightarrow y &= (2A-1)^{-\frac{\beta_W}{a\beta_x}} A^{\frac{\beta_A}{a\beta_x}} C + \frac{y\beta_W c(Q)}{(1-a)\beta_x c(Q) + \beta_W}; \\
\rightarrow \frac{y}{C} (1 - zP(q)\Delta) &= (2A-1)^{-\frac{\beta_W}{a\beta_x}} A^{\frac{\beta_A}{a\beta_x}}, \\
\text{where } \Delta &\equiv \beta_W \left(z((1-a)\beta_x c(Q) + \beta_W) \right)^{-1}.
\end{aligned}$$

Taking the log of the implicit function for A and totally differentiating yields an expression for the elasticity of A with respect to y :

$$\begin{aligned}
\ln y - \ln C + \ln \left(1 - \frac{\beta_W c(Q)}{(1-a)\beta_x c(Q) + \beta_W} \right) &= \frac{\beta_A}{a\beta_x} \ln A - \frac{\beta_W}{a\beta_x} \ln(2A-1); \\
\frac{1}{y} dy &= \left(\frac{\beta_A}{a\beta_x} \frac{1}{A} - \frac{\beta_W}{a\beta_x} \frac{2}{2A-1} \right) dA \rightarrow \frac{dA}{dy} = \frac{a\beta_x}{y} \left(\frac{\beta_A}{A} - \frac{2\beta_W}{2A-1} \right)^{-1}; \\
\frac{dA}{dy} < 0 &\leftrightarrow \frac{\beta_A}{\beta_W} < \frac{2A}{2A-1} \leftrightarrow A < \frac{\beta_A}{2(\beta_A - \beta_W)}; \\
\varepsilon_{Ay} &= \frac{dA}{dy} \frac{y}{A} = a\beta_x \left(\beta_A - \frac{2A\beta_W}{2A-1} \right)^{-1} = a\beta_x \left(\frac{2A-1}{(2A-1)\beta_A - 2A\beta_W} \right).
\end{aligned}$$

Finally, totally differentiating the equation relating W and $(2A - 1)$ and substituting for dA/dy yields an expression for the elasticity of W with respect to y :

$$W = y\Delta(2A-1);$$

$$\rightarrow \frac{dW}{dy} = 2y\Delta \frac{dA}{dy} + (2A-1) = 2y\Delta \frac{dA}{dy} + W \frac{1}{y\Delta};$$

$$\varepsilon_{Wy} = \frac{dW}{dy} \frac{y}{W} = \frac{A}{W} 2\Delta \varepsilon_{Ay} + \frac{1}{\Delta}.$$

The elasticity ε_{Wy} will be less than zero if $dA/dy < 0$:

$$\varepsilon_{Wy} < 0 \leftrightarrow A < \frac{\beta_A}{2(\beta_A - \beta_W)}.$$

Comparing the expressions for the elasticity of W with respect to y between equilibria yields a condition on the signaling equilibrium level of A that corresponds to ε_{Wy} being larger when there are social effects and A is the signaling variable than when $a = 0$:

$$\varepsilon_{Wy}|_{a=0} < \varepsilon_{Wy}|_{D_V=A} \leftrightarrow 1 < \frac{2a\beta_x A}{(2A-1)\beta_A - 2\beta_W A} + z \left((1-a) \frac{\beta_x}{\beta_W} c(Q) + 1 \right) \leftrightarrow Z < \frac{2a\beta_x A}{(2A-1)\beta_A - 2\beta_W A};$$

$$Z \equiv 1 - z \left((1-a) \frac{\beta_x}{\beta_W} c(Q) + 1 \right) < 0;$$

$$\leftrightarrow A > \frac{Z\beta_A}{2(Z(\beta_A - \beta_W) - a\beta_x)}; \text{ sign flips because } Z(\beta_A - \beta_W) - a\beta_x < 0.$$

Solution of equilibrium if the durable good is visible, $a > 0$, and $D_V = Q$

Let $h(Q)$ denote the equilibrium signaling function. The consumer's maximization problem is:

$$\begin{aligned} \max_{A, Q, W} U(A, Q, W) = & (1-a) \left(\beta_A \ln A + \beta_Q \ln Q + \beta_W \ln W + \beta_x \ln \left(y - zc(Q) \frac{W}{2A-1} \right) \right) \\ & + a \left(\beta_A \ln A + \beta_Q \ln Q + \beta_W \ln W + \beta_x \ln(h(Q)) \right). \end{aligned}$$

The first-order conditions for an interior equilibrium are:

$$(A): \frac{\beta_A}{A} = (1-a) \frac{\beta_x zc(Q)}{y - z \frac{W}{2A-1}} \left(\frac{2W}{(2A-1)^2} \right);$$

$$(Q): \frac{\beta_Q}{Q} - (1-a) \frac{\beta_x zW}{y - z \frac{W}{2A-1}} \left(\frac{c'(Q)}{2A-1} \right) + a \frac{\beta_x}{h(Q)} h'(Q) = 0;$$

$$(W): \frac{\beta_W}{W} = (1-a) \frac{\beta_x zc(Q)}{y - z \frac{W}{2A-1}} \left(\frac{1}{2A-1} \right).$$

Dividing the first-order condition for A by the condition for W yields an expression for A ; the first-order condition for W can be re-arranged and plugged into the condition for Q :

$$\begin{aligned}
\frac{W}{A} \frac{\beta_A}{\beta_W} &= \frac{2W}{(2A-1)} \rightarrow A = \frac{\beta_A}{2(\beta_A - \beta_W)}; \\
(1-a) \frac{\beta_x z}{y-z} \frac{W}{2A-1} &= \frac{\beta_W}{W} \frac{2A-1}{c(Q)}; \\
\rightarrow \frac{\beta_Q}{Q} - \beta_W \left(\frac{c'(Q)}{c(Q)} \right) + a \frac{\beta_x}{h(Q)} h'(Q) &= 0; \\
\rightarrow h'(Q) &= \frac{h(Q)}{a\beta_x} \left(\beta_W \frac{c'(Q)}{c(Q)} - \frac{\beta_Q}{Q} \right) = \frac{h(Q)}{a\beta_x} \left(\beta_W \delta_2 - \frac{\beta_Q}{Q} \right).
\end{aligned}$$

The general solution to the differential equation $h'(Q)$ can be solved using separation of variables:

$$\begin{aligned}
h'(Q) &= h(Q) \left(K + \frac{J}{Q} \right); \\
K &\equiv \frac{\beta_W \delta_2}{a\beta_x}; J \equiv \frac{\beta_Q}{a\beta_x}; \\
X \equiv h(Q) &\rightarrow \frac{dX}{dQ} = X \left(K + \frac{J}{Q} \right); \\
\frac{1}{X} dX &= \left(K + \frac{J}{Q} \right) dQ; \\
\ln X &= KQ + J \ln Q + \bar{B}; \\
\rightarrow \ln \frac{h(Q)}{Q^J} &= KQ + \bar{B}; \\
\rightarrow h(Q) &= Q^J \exp(KQ + \bar{B}); \\
B &\equiv \exp(\bar{B}); \\
h(Q) &= Q^{\frac{\beta_Q}{a\beta_x}} B \exp\left(Q \frac{\beta_W \delta_2}{a\beta_x}\right).
\end{aligned}$$

As above, the behavior of the lowest-type can be used to pin down the constant of integration:

$$\begin{aligned}
A &= \frac{\beta_A}{2(\beta_A - \beta_W)}; \\
W &= y \frac{\beta_W^2}{zc(Q)(\beta_x + \beta_W)(\beta_A - \beta_W)}; \\
Q &= \frac{c(Q)}{c'(Q)} \frac{\beta_Q}{\beta_W} = \frac{\beta_Q}{\delta_2 \beta_W}; \\
x &= y - zc(Q) \frac{W}{2A-1} = y \left(1 - \frac{\beta_W}{\beta_x + \beta_W} \right); \\
h(Q) &= Q^{\frac{\beta_A}{a\beta_x}} B \exp \left(Q \frac{\beta_W \delta_2}{a\beta_x} \right) = \left(\frac{\beta_Q}{\delta_2 \beta_W} \right)^{\frac{\beta_A}{a\beta_x}} B \exp \left(\frac{\beta_Q}{a\beta_x} \right); \\
h(Q) = x &\rightarrow B = y \left(\frac{\beta_x}{\beta_x + \beta_W} \right) \left(\frac{\beta_Q}{\delta_2 \beta_W} \right)^{-\frac{\beta_A}{a\beta_x}} \exp \left(-\frac{\beta_Q}{a\beta_x} \right) > 0.
\end{aligned}$$

Given the function $h(Q)$ and the equilibrium condition that $h(Q) = x$, we can plug in $h(Q)$ for x in the budget constraint and make use of the expression for W in terms of $(2A - 1)$ from the first-order condition for W to derive the implicit functions that define demand for Q and W :

$$\begin{aligned}
h(Q) &= Q^{\frac{\beta_Q}{a\beta_x}} B \exp \left(Q \frac{\beta_W \delta_2}{a\beta_x} \right); \\
y &= x + zc(Q) \frac{W}{2A-1}; \\
\frac{W}{2A-1} &= y\Delta; \\
\rightarrow y &= Q^{\frac{\beta_Q}{a\beta_x}} B \exp \left(Q \frac{\beta_W \delta_2}{a\beta_x} \right) + yzc(Q)\Delta; \\
Q : \frac{y}{B} \left(1 - \frac{c(Q)\beta_W}{((1-a)\beta_x c(Q) + \beta_W)} \right) &= Q^{\frac{\beta_Q}{a\beta_x}} \exp \left(Q \frac{\beta_W \delta_2}{a\beta_x} \right); \\
W : W &= y\Delta \left(\frac{\beta_W}{(\beta_A - \beta_W)} \right), \\
\text{where } \Delta &\equiv \beta_W \left(z((1-a)\beta_x c(Q) + \beta_W) \right)^{-1}.
\end{aligned}$$

We can take the log of the implicit function for Q and totally differentiate it to derive the elasticity of Q with respect to y :

$$\begin{aligned} \ln y - \ln B + \ln \left(((1-a)\beta_x - \beta_w)c(Q) + \beta_w \right) - \ln \left((1-a)\beta_x c(Q) + \beta_w \right) &= \frac{\beta_q}{a\beta_x} \ln Q + Q \frac{\beta_w \delta_2}{a\beta_x}; \\ \rightarrow \frac{1}{y} dy &= \left(\frac{\beta_q}{a\beta_x} \frac{1}{Q} + \frac{\beta_w \delta_2}{a\beta_x} - \beta_w^2 c'(Q) \frac{(1-a)\beta_x \beta_w c(Q) - \Delta z}{\Delta z (\Delta z - \beta_w^2 c(Q))} \right) dQ; \\ \varepsilon_{Qy} = \frac{dQ}{dy} \frac{y}{Q} &= \left(\frac{\beta_q}{a\beta_x} + Q \frac{\beta_w \delta_2}{a\beta_x} - Q \beta_w^2 c'(Q) \frac{(1-a)\beta_x \beta_w c(Q) - \Delta z}{\Delta z (\Delta z - \beta_w^2 c(Q))} \right)^{-1}. \\ \varepsilon_{Qy} > 0 &\Leftrightarrow \frac{\beta_q}{a\beta_x} (\Delta z - \beta_w^2 c(Q)) + Q \frac{\beta_w \delta_2}{a\beta_x} (\Delta z - \beta_w^2 c(Q)) > Q \beta_w^2 c'(Q) \frac{(1-a)\beta_x \beta_w c(Q)}{\Delta z} - Q \beta_w^2 c'(Q). \end{aligned}$$

Do the same for the implicit function for W , and substitute in the elasticity of Q :

$$\begin{aligned} W : (1-a)\beta_x z \delta_1 e^{\delta_2 Q} W + \beta_w z W &= y \left(\frac{\beta_w^2}{(\beta_A - \beta_w)} \right); \\ \rightarrow (z(1-a)\beta_x c(Q) + z\beta_w) dW &+ (1-a)\beta_x z \delta_2 W c(Q) dQ = \left(\frac{\beta_w^2}{(\beta_A - \beta_w)} \right) dy; \\ \rightarrow \frac{dW}{dy} &= \left(\frac{\beta_w^2}{(\beta_A - \beta_w)} \right) - \frac{(1-a)\beta_x \delta_2 c(Q)}{(1-a)\beta_x c(Q) + \beta_w} W \frac{dQ}{dy}; \\ \varepsilon_{Wy} = \frac{dW}{dy} \frac{y}{W} &= \frac{y}{W} \left(\frac{\beta_w^2}{\beta_A - \beta_w} \right) - Q \delta_2 \frac{(1-a)\beta_x c(Q)}{(1-a)\beta_x c(Q) + \beta_w} \varepsilon_{Qy}. \end{aligned}$$

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